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TECHNICAL REPORT NO. LWL-CR-06-RAB

A REPORT ON THE PERFORMANCE CHARACTERISTICS OF POWER SOURCES FOR REMOTE AREAS

Final Report
Contract No. DAAD05-68-C-0178

By

Booz - Allen Applied Research, Inc.
4733 Bethesda Avenue
Bethesda, Maryland

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ABSTRACT

This report summarizes performance characteristics of candidate power sources planned particularly for use by indigenous forces of friendly, underdeveloped nations. Older types of power sources, such as heat engines, hydroelectric and magnetohydrodynamic, are suggested for continued research and development. Newer concepts, such as fuel cells, thermoelectric, thermionic and solar, are investigated for special applications. A table which summarizes in detail the status of technologic development of power sources is included.

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FOREWORD

This report was prepared in compliance with Work Assignment No. 4, Contract No. DAAD05-68-C-0178. The objective of the work assignment was to determine what power levels and other performance characteristics can be achieved for remote areas with various power sources currently in state-of-the-art, development, and planning stages. The power sources of interest range from a few watts to two or three kilowatts of power output.

I. INTRODUCTION

Special and counterinsurgency forces of the U. S. Army are employed primarily to assist indigenous forces of friendly underdeveloped nations in self-development. A basic requirement for national development is electrical power. Initial electrical power requirements need not be for large quantities but, rather, may be only for vital services such as communications and medical care. Since the term "underdeveloped" connotes a restricted transportation system and the absence of a national electrical distribution system, emphasis must be placed upon localized sources, use of indigenous fuels, simple maintenance, and a minimal requirement for repair parts. Efficiency becomes a minor criterion; what is far more important is the impact of fuel and spare parts requirements upon the national economy. Inefficient use of cheap, locally available fuel — for example, alcohol — may be of greater benefit than efficient use of imported fuel which adds to a strained balance of trade.

As the economy of a nation grows, the transportation system must also grow. Power requirements for transportation then must be added to those of vital services. The foregoing criteria remain important, nevertheless. That is, those power sources which offer the greatest benefit and are least expensive should be sought. In fact, in view of the growing shortage of copper,[1] one might predict that the massive electrical distribution systems of the United States and Western Europe will not be duplicated. Austere systems will be developed which will minimize the use of copper, of course. However, these systems will be costly and development and installation will be time-consuming.

It is well to note that even in the United States, with its extensive electrical distribution system, the commercial market for local electrical power sources in remote areas continues to expand. Examples of such use are power for remote automatic weather stations, remote microwave relay stations, and, perhaps more surprising, radio and lighting for the caboose of freight trains.

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1 / National Resources - A Summary Report, NAC-NRC Publication, 1000, November 1962, F. Seitz.

Electrical power requirements in the lower range of power outputs can conveniently be grouped in three categories: outputs from less than one watt to a few, say 50 or 60, watts; outputs from a few watts to about one kilowatt; and outputs from about one kilowatt upwards to about two or three kilowatts. These categories are considered somewhat arbitrary and have not constrained the present survey except as they establish the order of magnitude of the output range of interest.

Power of a few watts is adequate for small communication receivers and transmitters. Power up to about one kilowatt is adequate for larger communication apparatus, for microwave relay stations, and for related applications, including small refrigeration units. Power of more than one kilowatt is, of course, needed for heavier service applications.

In the range of power outputs of interest, there are several power system options available, some with several energy sources. Table 1[2] provides a broad overview of the state-of-the-art of several candidate types of devices. This table attempts to portray the status of energy systems as of the 1964 time frame. One should note the cost of power generation indicated in Table 1 with some caution. Costs indicated are at the source; distribution costs in the United States normally range from 3 to 20 times the cost at source. A similar report[3] prepared by the National Aeronautics and Space Administration in 1967 indicates that NASA has reduced some 30-50 candidate types of systems to 15 of greatest interest. These 15 are illustrated in Figure 1. The NASA report concludes that development of 15 candidates would require excessive financial support and further reduces them to a total of eight as illustrated in Figure 2. These eight candidate system types will receive primary development support from NASA over the next several years.

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2 / Energy R&D and National Progress, prepared for the Interdepartmental Energy Study by the Energy Study Group, Office of Science and Technology, 1964.

3 / Transcript of the Briefing for Industry on NASA Space Power and Electric Propulsion Programs, National Aeronautics and Space Administration, April 1967.

TABLE 1- —*Status of technologic development of energy devices* [1]

Name	Description of device: Primary application	Description of device: Resources input (form of energy)	Description of device: Type output (form of energy)	Description of device: Scaling range	State of technology: State of R&D or technology [2]	State of technology: Current engineering efficiency	State of technology: Possible engineering efficiency	State of technology: Limiting phenomena and required research	Performance: Specific power of device: Watts/ft^3 (except as noted)	Performance: Specific power of device: Watts/lb (except as noted)	Performance: Reliability	Performance: Present life	Performance: Future life
HEAT ENGINES	Transportation and power generation.	Chemical fossil fuels (except as noted).	Mechanical (except as noted).	Noted below	Noted below	At point of maximum efficiency.	Only minor improvements in efficiency are expected.	Research to understand combustion, ignition, and preignition phenomena for nonnuclear fuels.			Unlimited		Has been increasing.
Diesel	Transportation; Power generation	Fossil fuel		5-25,000 hp	Stage 5	35-38 percent (600 hp).		Study how to control wear and to improve air-fuel mixture.		41-187 (600 hp); 62-187 (600 hp)		40,000 hours (automotive). 20 years (stationary).	
Otto	Transportation	do.		½-3,500 hp	do.	28 percent (350 hp).		Learn how to improve uniformity of fuel-air mixture.	75 kw/ft^3 (airplane).	250-746		250 hours (maximum power), 2,000 hours (half power).	
Two stroke	do.	do.		Fractional to 100 hp.	do.	15-20 percent				370 (example)			
Gas turbine	do.; Power generation	do.		100-67,000 hp (138,000-hp turbine planned).	do.	25-30 percent (350 hp).		Reduce cost, find inexpensive metals with long life at high temperatures. Develop highly reliable regenerative heat exchangers.[*] Develop near isothermal turbo compressers.[3]	750 kw/ft^3 (airplane jet engine).	300-620		2,000 hours (automotive). 10 years (stationary).	
Stirling	Auxiliary power space application.	Heat source (external-combustion engine).		Unknown	Stage 3	40 percent (100 hp/cylinder).		Reduce weight.		67-95			
Free-piston gas turbine.	Power generation	Fossil fuel		do.	do.	35 percent (1,000 hp/cylinder).				62 (example)			
Wankel	Transportation	do.		10-50 hp	Stage 4	18-25 percent (150 hp).		Improve sealing in combustion chamber.		370 (example)			
Steam plant (conventional, natural gas-fired).	Power generation	Natural gas	Electrical AC	Within limits, efficiency increases with size. 500 kw-1,500 Mw	Stage 5	32 percent average 48.8 percent maximum (estimates for 1980).	38.3 percent average 48.8 percent maximum (estimates for 1980).	Develop ways to reduce boiler maintenance costs. Find cheaper ways to control air pollution. Improvement of methods of fabrication of good quality large-size parts for steam turbines.	Not applicable	Not applicable		Depends on economic considerations	
Steam plant (conventional, coal-fired).	do.	Coal	do.					Improvements of materials so that it will become economical to increase boiler pressure, initial superheat, and condenser vacuum.	do.	do.		do.	
Steam plant (combined cycle, gas and steam turbine).	do.	Natural gas	do.	17. Mw-213 Mw	do.	4- to 6-percent increase over steam.			do.	do.		do.	
Mercury-steam	do.	Coal, natural gas, oil	do.	1,500 kw-40 Mw	do.	25-percent increase over steam.		Not economically feasible at present time. High cost of plant construction and high cost of mercury.	do.	do.		do.	
Steam plant (nuclear reactor).	do.	Uranium, thorium	do.		Stage 4		Presently 32 percent [8] (estimated for lightwater reactor); above 40 percent in 1980.	Fuel performance—Accumulate statistical data on which to base rigorous yet economic material and manufacturing process specifications for both zirconium and stainless steel-clad uranium oxide fuels. Work to lower fuel fabrication costs. Demonstration of ability to recycle plutonium in present power reactors. System dynamics—Interaction between reactor power level, load demand, power density, fuel exposure, coolant flow, and control system characteristics. Improve instrumentation. Plant compaction and simplification of core, shielding, cooling, and problems of heat transfer and fluid flow. Breeder reactor development.	do.	do.		do.	
HYDROELECTRIC	Power generation. Secondary benefits that may result: Flood control; irrigation; navigation; recreation.	Mechanical	Electrical, AC or DC.		Stage 5	Hydraulic turbine efficiency approximately 93 percent.	Only minor improvements in efficiency are expected.		do.	do.	Excellent	Unlimited	Not applicable
Reversible or pumped storage type		Water power and electric energy in reverse cycle.		240 Mw [9], largest existing plant.									
Straight hydroelectric generator.		Water power		1,974 Mw,[10] largest existing plant.									
MAGNETOHYDRODYNAMICS	Direct generation of electrical energy.	The MHD generator extracts mechanical energy from the moving conducting fluid and delivers an electrical energy output. Mechanical and thermal energy is delivered to the fluid by a combustor or reactor and a nozzle. The system concept is considered below and the listed input energy is in the form of combustor or reactor fuel.	Electrical DC (except as noted). Voltages in the kilovolt range.	Efficiency increases with size. Limit to how small a unit can be and still provide enough power for magnetic field.[12]	Noted below	Noted below (where available).	Noted below (where available).		Not applicable in general to laboratory models.	Not applicable in general to laboratory models.	Not established. Potentially good.	Short	Not established. Potentially good.
Open cycle		Fossil fuel: Powdered coal or hydrocarbons.			Stage 2			Need to develop economical long-life electrodes. Need to develop superconducting magnets. Study electrical conductivity in gases. A search for superior seed material. Refinement of present values for collision cross sections in					

TABLE 1- —*Status of technologic development of energy devices* [1]

	Description of device				State of technology				Performance					Economics			
									Specific power of device					Capital costs		Power costs	
	Primary application	Resources input (form of energy)	Type output (form of energy)	Scaling range	State of R&D or technology [2]	Current engineering efficiency	Possible engineering efficiency	Limiting phenomena and required research	Watts/ft^3 (except as noted)	Watts/lb (except as noted)	Reliability	Present life	Future life	Present	Future	Present	Future
NES	Transportation and power generation.	Chemical fossil fuels (except as noted).	Mechanical (except as noted).	Noted below	Noted below	At point of maximum efficiency.	Only minor improvements in efficiency are expected.	Research to understand combustion, ignition, and preignition phenomena for nonnuclear fuels.			Unlimited		Has been increasing.				Should not change too much because technological advances are balanced by increasing fuel costs.
	Transportation Power generation	Fossil fuel		5-25,000 hp	Stage 5	35-38 percent (600 hp).		Study how to control wear and to improve air-fuel mixture.		41-187 (600 hp) 62-187 (600 hp)		40,000 hours (automotive). 20 years (stationary).		$300/kw ($500/kw, small-size unit).		7 mills/kwh	
	Transportation	do		½-3,500 hp	do	28 percent (350 hp).		Learn how to improve uniformity of fuel-air mixture.	75 kw/ft^3 (airplane).	250-746		250 hours (maximum power), 2,000 hours (half power).		$3/kw (mass produced) $140/kw (large utility type).		30 mills/kwh	
e	do	do		Fractional to 100 hp.	do	15-20 percent				370 (example)				Vary widely from range of Otto to diesel.	20 percent larger than Otto.		
e	do Power generation	do		100-67,000 hp (138,000-hp turbine planned).	do	25-30 percent (350 hp).		Reduce cost, find inexpensive metals with long life at high temperatures. Develop highly reliable regenerative heat exchangers. Develop near isothermal turbo compressors.[3]	750 kw/ft^3 (airplane jet engine).	300-620		2,000 hours (automotive). 10 years (stationary).		$100-$125/kw (7-25-Mw package unit). $300/kw (500 kw stationary).	$30/kw (forecast for mass-produced automobile turbine).	7-15 mills/kwh	
	Auxiliary power space application.	Heat source (external-combustion engine).		Unknown	Stage 3	40 percent (100 hp/cylinder).		Reduce weight.		67-95					Comparable with turbine.		
gas	Power generation	Fossil fuel		do	do	35 percent (1,000 hp/cylinder).				62 (example)					do		
	Transportation	do		10-50 hp	Stage 4	18-25 percent (150 hp).		Improve sealing in combustion chamber.		370 (example)					10 percent larger than Otto.		
it (con-, nat-, ired).	Power generation	Natural gas	Electrical AC	Within limits, efficiency increases with size. 500 kw-1,500 Mw	Stage 5	32 percent average 48.8 percent maximum (estimates for 1980).	38.3 percent average 48.8 percent maximum (estimates for 1980).	Develop ways to reduce boiler maintenance costs. Find cheaper ways to control air pollution. Improvement of methods of fabrication of good quality large-size parts for steam turbines. Improvements of materials so that it will become economical to increase boiler pressure, initial superheat, and condenser vacuum.	Not applicable	Not applicable		Depends on economic considerations		$105/kw [4] $110-$125/kw [7]		3.69 mills/kwh [4,5] 5.02 mills/kwh [4,6] 4.11 mills/kwh [7] (750-Mw plant)	Continuing progress in reducing steam electric power costs appears likely, due to new large plants going into service.
t (con-, coal-	do	Coal	do						do	do		do		$120/kw [4] $120-$150/kw [7]	$129/kw [8]	3.99 mills/kwh [4,5] 5.28 mills/kwh [4,6] 4.64 mills/kwh [7] (1,440-Mw plant)	Do.
t (com-, le, gas, n tur-	do	Natural gas	do	17. Mw-213 Mw	do	4- to 6-percent increase over steam.			do	do		do		$105/kw [4]		3.69 mills/kwh [4,5] 4.92 mills/kwh [5,6]	
eam	do	Coal, natural gas, oil	do	1,500 kw-40 Mw	do	25-percent increase over steam.		Not economically feasible at present time. High cost of plant construction and high cost of mercury.	do	do		do		$317/kw [7]			
t (nu-, tor).	do	Uranium, thorium	do		Stage 4		Presently 32 percent [9] (estimated for lightwater reactor); above 40 percent in 1980.	Fuel performance—Accumulate statistical data on which to base rigorous yet economic material and manufacturing process specifications for both zirconium and stainless steel-clad uranium oxide fuels. Work to lower fuel fabrication costs. Demonstration of ability to recycle plutonium in present power reactors. System dynamics—Interaction between reactor power level, load demand, power density, fuel exposure, coolant flow, and control system characteristics. Improve instrumentation. Plant compaction and simplification of core, shielding, cooling, and problems of heat transfer and fluid flow. Breeder reactor development.	do	do		do			$165/kw [4] $175/kw [8]		Do.
CTRIC	Power generation. Secondary benefits that may result: Flood control; irrigation; navigation; recreation.	Mechanical	Electrical, AC or DC.		Stage 5	Hydraulic turbine efficiency approximately 93 percent.	Only minor improvements in efficiency are expected.		do	do	Excellent	Unlimited	Not applicable			Not applicable	Not applicable.
or storage		Water power and electric energy in reverse cycle.		240 Mw [9], largest existing plant.										$75-$125/kw			
dro- nerator.		Water power		1,974 Mw, [10] largest existing plant.										Range [11] from $400/kw (15Mw plant) to $110/kw (large plant over 100 Mw)			
YDRO- 3	Direct generation of electrical energy.	The MHD generator extracts mechanical energy from the moving conducting fluid and delivers an electrical energy output. Mechanical and thermal energy is delivered to the fluid by a combustor or reactor and a nozzle. The system concept is considered below and the listed input energy is in the form of combustor or reactor fuel.	Electrical DC (except as noted). Voltages in the kilovolt range.	Efficiency increases with size. Limit to how small a unit can be and still provide enough power for magnetic field.[12]	Noted below	Noted below (where available).	Noted below (where available).	Need to develop economical long-life electrodes. Need to develop superconducting magnets. Study electrical conductivity in gases.	Not applicable in general to laboratory models.	Not applicable in general to laboratory models.	Not established. Potentially good.	Short	Not established. Potentially good.	Not established		Not established	
		Fossil fuel: Powdered coal or hydrocarbons.			Stage 2			A search for superior seed material. Refinement of present values for collision cross sections in									

ventional, coal-fired).	do	Coal	do	Mw				Improvements of materials so that it will become economical to increase boiler pressure, initial superheat, and condenser vacuum.	do	do	
Steam plant (combined cycle, gas and steam turbine).	do	Natural gas	do	17. Mw–213 Mw	do	4- to 6-percent increase over steam.			do	do	
Mercury-steam	do	Coal, natural gas, oil	do	1,500 kw–40 Mw	do	25-percent increase over steam.		Not economically feasible at present time. High cost of plant construction and high cost of mercury.	do	do	
Steam plant (nuclear reactor).	do	Uranium, thorium	do		Stage 4		Presently 32 percent[8] (estimated for lightwater reactor); above 40 percent in 1980.	Fuel performance—Accumulate statistical data on which to base rigorous yet economic material and manufacturing process specifications for both zirconium and stainless steel-clad uranium oxide fuels. Work to lower fuel fabrication costs. Demonstration of ability to recycle plutonium in present power reactors. System dynamics—Interaction between reactor power level, load demand, power density, fuel exposure, coolant flow, and control system characteristics. Improve instrumentation. Plant compaction and simplification of core, shielding, cooling, and problems of heat transfer and fluid flow. Breeder reactor development.	do	do	
HYDROELECTRIC	Power generation. Secondary benefits that may result: Flood control; irrigation; navigation; recreation.	Mechanical	Electrical, AC or DC.		Stage 5	Hydraulic turbine efficiency approximately 93 percent.	Only minor improvements in efficiency are expected.		do	do	Excellent
Reversible or pumped storage type		Water power and electric energy in reverse cycle.		240 Mw[9], largest existing plant.							
Straight hydroelectric generator.		Water power		1,974 Mw,[10] largest existing plant.							
MAGNETOHYDRODYNAMICS	Direct generation of electrical energy.	The MHD generator extracts mechanical energy from the moving conducting fluid and delivers an electrical energy output. Mechanical and thermal energy is delivered to the fluid by a combustor or reactor and a nozzle. The system concept is considered below and the listed input energy is in the form of combustor or reactor fuel.	Electrical DC (except as noted). Voltages in the kilovolt range.	Efficiency increases with size. Limit to how small a unit can be and still provide enough power for magnetic field.[13]	Noted below	Noted below (where available).	Noted below (where available).	Need to develop economical long-life electrodes. Need to develop superconducting magnets. Study electrical conductivity in gases. A search for superior seed material. Refinement of present values for collision cross sections in gases of interest. Problem of chemical interactions between seed materials and uncooled wall insulation. Engineering and economic studies of overall-plant or propulsion-system design.	Not applicable in general to laboratory models.	Not applicable in general to laboratory models.	Not established Potentially go
Open cycle		Fossil fuel: Powdered coal or hydrocarbons.			Stage 2						
As topping unit.	Bulk power generation.			500-Mw unit being studied.	Design		53 percent (estimated) 40 percent steam plant, 70 percent MHD power.				
		Typical laboratory units.		5 Mw (net)	do	Estimated 2.5 percent.[14]					
		Kerosene or residual fuel oil and seed.									
As single system.	Space power, military applications and laboratory tests.	JP-4, O_2, and seed		1.5 Mw (gross)	Tested	Approximately 5 percent.[14]					
		Ethyl alcohol, O_2 and seed.		20 Mw	Design	Estimated 5.5 percent.[14]				0.1[12, 15]	
		Diesel fuel, N_2, O_2, and seed.[16]		7.9 Kw	Tested						
		Kerosene, ethanol, N_2, O_2, and seed.[16]		1.03 Kw	do	2 percent					
Space propulsion.	Thrust	DC electrical; AC electrical	Mechanical	Approx. 0.05–1 lb thrust of laboratory devices.	Stage 2	10–70 percent estimated maximum effect of laboratory devices.					
		Nuclear fission fuels	do		Preliminary calculations.[17]	Approximately 70 percent (estimated overall efficiency).				Thrust-to-weight ratio of 10.	

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vide enough ver for mag- ic field.[13]									
	Stage 2			Need to develop economical long-life dectrodes. Need to levelop supercon- ducting nagnets. Study elecrical conductivity in gases. A search for superior seed material:. Refinemert of present values for collison cross sections in gases of nterest. Problem f chemical inter- actions between seed ma- terials and uncooled wall insulation. Engineering and economic studies f overall-plant or propulsion-system design.					
w unit g studied.	Design		53 percent (esti- mated) 40 percent steam plant, 70 per- cent MHD power.						
(net)	do	Estimated 2.5 percent.[14]							
w (gross)	Tested	Approximately 5 percent.[14]						20 seconds	
r	Design	Estimated 5.5 percent.[14]				0.1[13 15]		3 minutes	
r	Tested							10 minutes	
w	do	2 percent						30 minutes	
x. 0.05-1 lb st of lab- ry devices.	Stage 2	10-70 percent es- timated maxi- mum effect of laboratory de- vices.							
	Preliminary cal- culations.[17]	Approximately 70 percent (esti- mated overall efficiency).				Thrust-to-weight ratio of 10.			

						Not established		Not established. (Estimates have been made.[5,6,13])
						do		Do.[5,6,13]
			20 seconds					
	0.1 [13,15]		3 minutes					
			10 minutes					
			30 minutes					
	Thrust-to-weight ratio of 10.							

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Table I - Continued —*Status of technologic development of energy devices* [1]

Name	Description of device: Primary application	Description of device: Resources input (form of energy)	Description of device: Type output (form of energy)	Description of device: Scaling range	State of technology: State of R&D or technology [2]	State of technology: Current engineering efficiency	State of technology: Possible engineering efficiency	State of technology: Limiting phenomena and required research	Performance: Specific power of device: Watts/ft³ (except as noted)	Performance: Specific power of device: Watts/lb (except as noted)	Performance: Reliability	Performance: Present life	Performance: Future life	Economics: Capital costs: Present	Economics: Capital costs: Future	Economics: Pr
Closed cycle	Bulk or space power generation with nuclear reactor.	Nuclear fission fuels		Laboratory models in the Mw range are being constructed.	Stage 2		40 percent (estimated) (No turbine). 50 percent (estimated) (nuclear MHD-steam closed cycle powerplant).[18]	Must find low-temperature (less than 2,500° F) conducting fluid. Research: Nonequilibrium ionization. Recombination rates. Interaction between electromagnetic radiation and electron beams, with plasma. Liquid metals. Impurity problems. Seeding problems. Pumping problems								
Vortex type	Bulk power. Space power	Fossil fuels. Nuclear fission fuels			Stage 1											
AC type	Bulk power. Space power	Fossil fuels. Nuclear fission fuels	Electrical AC		do											
EHD	Power generation	Fossil fuels. Nuclear fission fuels	Electrical DC, very high voltage, Mv range, and very low currents.	Not established	do	Not established for complete energy conversion system.	Not established for complete energy conversion system.									
FUEL CELLS	Direct generation of electrical energy. Moderate size power requirements. General uses of fuel cells: auxiliary power supplies for industrial, military and underdeveloped countries. (to replace batteries). Motive power for special applications.	Chemical—Gas or liquid.	Electrical DC, low voltage, high current.	Efficiency is independent of size. Sizes, 20w-5kw.	Several units have been tested in laboratory. Several prototype units to be ready in from 2 to 5 years.	Examples noted below.	40-80 percent (estimated).		0.5-5 kw/ft³	5-40	Not established	Thousands of hours for some units. Hundreds of hours for other devices.	1 year (estimated)	$47,000/kw (Gemini).	Few hundred dollars per kilowatts (estimated minimum cost).	High
Primary: Low temperature (<150° F).		H_2-O_2			Stage 3			Need for qualified electrochemists. Basic research on catalysis and electrode mechanisms. Research on interstitial and/or substitutional alloys. Development of stable conductive membrane electrolytes or use at low and intermediate temperatures. Research on molten-salt electrolytes for use at intermediate temperatures. Study methods of producing novel fuels characterized by high electrochemical reactivity combined with potentially low cost. Develop high power density space cellusing alkali metals. Microbiology research to study potential of biochemical fuel cells. Develop corrosion-resistant materials for low temperature acid electrolyte cells. Develop materials for high temperature cells. Research to study: Heat transfer. Mass transfer. Catalyst recovery and regeneration. Fuel purification.	0.5-1 kw/ft³ (including auxiliaries).	7-12 (including auxiliaries).		4,000 hours (laboratory tests).				
		H_2-air							0.5 kw/ft³			200 hours (laboratory tests).				
		Alcohol-air			Stage 2											
		Ammonia-O_2														
		Hydrocarbons-air			Stage 1											
Intermediate temperature (<400° F).		H_2-O_2			Stage 3	70 percent										
		H_2-air														
		Alcohol-air, ammonia-air			Stage 2											
		Hydrocarbons-air			Stage 1											
High temperature (<800° F).		H_2-O_2			Stage 2											
		H_2-air			do											
		CO-O_2			do											
		Hydrocarbons-air			do							400 hours (laboratory tests).				
Very high temperature (>800° F).		C-O_2										200-800 hours (laboratory tests).				
Secondary		Fuel cell reactants can be regenerated by electricity, heat, light, and radioactivity.			Stage 1											
		Elec. regenerative			do		65 percent maximum (estimate).									
Low temperature.		H_2-O_2			do											
		K-Hg			do							600 hours (laboratory tests).				
		Thermo. regenerative			do											
		Antimony-chloride			do											
		$PbCl_2$ membrane			do	15-30 percent										
Intermediate temperature.					do				10 kw/ft³	30						
High temperature.		K-Hg			do							550 hours (laboratory tests).				
Biochemical:					do		Unknown									
Direct					do											
Indirect					do											
Pseudo					do											
In vivo	For supplying power in the human body.				do											
THERMO-ELECTRIC	Direct generation of electric power for special applications. Example: Replace batteries for danger signals, radios, furnace fans, or vehicle radar.	See below	Electrical DC, high current, low voltage.	Efficiency relatively independent of size.	Fair theory. Much empirical R&D.	1-6 percent	Maximum 10 percent (estimated).				Potentially better than other conversion methods with moving parts.		5-10 years (estimated).			
Seebeck devices	Marine and terrestrial.	Natural gas		4-15 watts	Stages 2,3,4,5	1-6 percent		Theoretical studies aimed at determining relationships among fundamental parameters. Example: Electrical transport and lattice thermal transport. Study of materials (alloying, etc.) in a program which is consistant with the theory program. Study of the effects of inhomogeneities in thermoelectric materials with development of improved methods of detection, elimination, and possible exploration. Behavior of materials over larger temperature range. Corrosion of materials. Theoretical study to see if there is an upper limit to Z.						4-15 watt commercial device $30/watt (estimated).		Estimat[e] on $2-[…] $30/watt amorti[zed] 5-year
		Propane	Example design (28 volts and about 10 amp).	4-267 watts	do	1.4-3 percent				5 (Typ) (w/5 lb fuel).						
		Gasoline		45-150 watts	Stages 2,3,4				150	8 (Typ) (Includes fuel for 8 hours.)						
		Diesel		5 kw	Stage 2					10						
	Space and marine	Radioisotopes		4-125 watts	Stages 2, 3, 4	4-6 percent	8-11 percent (estimate for 1975).			Laboratory generator w/o isotope.		1 year, design. 2 year, minimum 2 year, design 2 year, life.	Greater than 5 years.		$25/kw. Estimate for 1975, does not include isotope.	$11.5/kw[…] device[…] $1.15/kw[…] device) […] mate f[…] curren[…] develo[…]
	Space	Nuclear reactor		Approximately	Stages 2, 3	1.7 percent (esti-	5-8 percent (esti-			15.5-50 [12]			Greater than 5		$25/kw. Estimate	

Table I - Continued —*Status of technologic development of energy devices*[1]

of device		State of technology				Performance					Economics			
						Specific power of device					Capital costs		Power costs	
Type output (form of energy)	Scaling range	State of R&D or technology[3]	Current engineering efficiency	Possible engineering efficiency	Limiting phenomena and required research	Watts/ft[3] (except as noted)	Watts/lb (except as noted)	Reliability	Present life	Future life	Present	Future	Present	Future
	Laboratory models in the Mw range are being constructed.	Stage 2		40 percent (estimated) (No turbine). 50 percent (estimated) (nuclear MHD-steam closed cycle powerplant).[18]	Must find low-temperature (less than 2,500° F) conducting fluid Research: Nonequilibrium ionization Recombination rates Interaction between electromagnetic radiation and electron beams, with plasma. Liquid metals Impurity problems Seeding problems Pumping problems									
		Stage 1												
Electrical AC		do												
Electrical DC, very high voltage, Mv range, and very low currents.	Not established	do	Not established for complete energy conversion system.	Not established for complete energy conversion system.										
Electrical DC, low voltage, high current.	Efficiency is independent of size. Sizes, 20w-5kw.	Several units have been tested in laboratory. Several prototype units to be ready in from 2 to 5 years.	Examples noted below.	40-80 percent (estimated).	Need for qualified electrochemists Basic research on catalysis and electrode mechanisms. Research on interstitial and/or substitutional alloys. Development of stable conductive membrane electrolytes for use at low and intermediate temperatures. Research on molten-salt electrolytes for use at intermediate temperatures. Study methods of producing novel fuels characterized by high electrochemical reactivity combined with potentially low cost. Develop high power density space cells using alkali metals. Microbiology research to study potential of biochemical fuel cells. Develop corrosion-resistant materials for low temperature acid electrolyte cells. Develop materials for high temperature cells. Research to study: Heat transfer. Mass transfer. Catalyst recovery and regeneration. Fuel purification.	0.5-5 kw/ft³	5-40	Not established	Thousands of hours for some units. Hundreds of hours for other devices.	1 year (estimated).	$47,000/kw (Gemini).	Few hundred dollars per kilowatts (estimated minimum cost).	High	34 mills/kwh (estimate based on 1-year life and $300/kw capital costs).
		Stage 3				0.5-1 kw/ft³ (including auxiliaries).	7-12 (including auxiliaries).		4,000 hours (laboratory tests).					
		Stage 2				0.5 kw/ft³			200 hours (laboratory tests).					
		Stage 1												
		Stage 3	70 percent											
		Stage 2												
		Stage 1												
		Stage 2												
		do												
		do												
		do							400 hours (laboratory tests).					
									200-800 hours (laboratory tests).					
		Stage 1												
		do		65 percent maximum (estimate).										
		do												
		do							600 hours (laboratory tests).					
		do												
		do												
		do	15-30 percent											
		do				10 kw/ft³	30							
		do							550 hours (laboratory tests).					
		do		Unknown										
		do												
		do												
		do												
		do												
Electrical DC, high current, low voltage.	Efficiency relatively independent of size.	Fair theory. Much empirical R&D.	1-6 percent	Maximum 10 percent (estimated).	Theoretical studies aimed at determining relationships among fundamental parameters. Example: Electrical transport and lattice thermal transport. Study of materials (alloying, etc.) in a program which is consistant with the theory program. Study of the effects of inhomogeneities in thermoelectric materials with development of improved methods of detection, elimination, and possible exploration. Behavior of materials over larger temperature range. Corrosion of materials. Theoretical study to see if there is an upper limit to Z.			Potentially better than other conversion methods with moving parts.		5-10 years (estimated).				Not established.
	4-15 watts	Stages 2,3,4,5	1-6 percent								4-15 watt commercial device $30/watt (estimated).		Estimate based on $2-$3/kwh. $30/watt device amortized over 5-year period.	
Example design (28 volts and about 10 amp).	4-267 watts	do	1.4-3 percent				5 (Typ) (w/5 lb fuel).							
	45-150 watts	Stages 2,3,4				150	8 (Typ) (Includes fuel for 8 hours.)							
	5 kw	Stage 2												
	4-125 watts	Stages 2, 3, 4	4-6 percent	8-11 percent (estimate for 1975).			10. Laboratory generator w/o isotope.		1 year, design 2 year, minimum 2 year, design 2 year, life.	Greater than 5 years.		$25/kw. Estimate for 1975, does not include isotope.	$11.5/kwh (10 watt device). $1.15/kwh (1 kw device) (estimate for device currently under development).	
	[illegible]	Stages 2, 3	[illegible]	[illegible]			15.5-50 [illegible]			Greater than 5 [illegible]		$25/kw. Estimate [illegible]		

2

	C-O2						Develop high-power … space cellusing alkali metals. Microbiology research to study potential of bio-chemical fuel cells. Develop corrosion-resistant materials for low temperature acid electrolyte cells. Develop materials for high temperature cells. Research to study: Heat trasfer. Mass trasfer. Catalyst recovery and regeneration. Fuel purification.				200-800 hours (laboratory tests).				
	Fuel cell reactants can be regenerated by electricity, heat, light, and radioactivity.			Stage 1											
	Elec. regenerative			do.		65 percent maximum (estimate).									
	H_2-O_2			do.							600 hours (laboratory tests).				
	K-Hg			do.											
	Thermo. regenerative			do.											
	Antimony-chloride			do.											
	$PbCl_2$ membrane			do.	15-30 percent			10 kw/ft³	30						
				do.							550 hours (laboratory tests).				
	K-Hg			do.											
				do.		Unknown									
				do.											
				do.											
				do.											
				do.											
For supplying power in the human body. Direct generation of electric power for special applications. Example: Replace batteries for danger signals, radios, furnace fans, or vehicle radar.	See below	Electrical DC, high current, low voltage.	Efficiency relatively independent of size.	Fair theory. Much empirical R&D.	1-6 percent	Maximum 10 percent (estimated).	Theoretical studies aimed at determining relationships among fundamental parameters. Example: Electrical transport and lattice thermal transport. Study of materials (alloying, etc.) in a program which is consistant with the theory program. Study of the effects of inhomogeneities in thermoelectric materials with development of improved methods of detection, elimination, and possible exploration. Behavior of materials over larger temperature range. Corrosion of materials. Theoretical study to see if there is an upper limit to Z.			Potentially better than other con version methods with moving parts.		5-10 years (estimated).			
	Natural gas		4-15 watts	Stages 2,3,4,5	1-6 percent								4-15 watt commercial device $30/watt (estimated).		Estim on $ $30/w amc 5-y
Marine and terrestrial.	Propane	Example design (28 volts and about 10 amp).	4-267 watts	do.	1.4-3 percent				5 (Typ) (w/5 lb fuel).						
	Gasoline		45-150 watts	Stages 2,3,4				150	8 (Typ) (Includes fuel for 8 hours.)						
	Diesel		5 kw	Stage 2					10						
Space and marine	Radioisotopes		4-125 watts	Stages 2, 3, 4	4-6 percent	8-11 percent (estimate for 1975).			Laboratory generator w/o isotope.		1 year, design. 2 year, minimum 2 year, design 2 year, life.	Greater than 5 years.		$25/kw. Estimate for 1975, does not include isotope.	$11.5/l dev $1.15/l devi mat curr dev
Space	Nuclear reactor		Approximately 500 watts under development. Estimated 100 kw in 1975.	Stages 2, 3	1.7 percent (estimate).	5-8 percent (estimate for 1975).			15.5-50 [19] Combined generator, does not include reactor shielding.[19]			Greater than 5 years (1975).		$25/kw. Estimate for 1975.	
	Solar radiation			Stages 2, 3, 4											
	Flat plate radiation		0.1-10 kw (estimate).		1.5 percent	6-8 percent (estimate for 1975).		2 watts/ft²	15-20 w/o system deploy and support structure.		1 year (10 percent degradation, laboratory test). Poor in flight tests.	Greater than 5 years (1975).	Not established	$25/kw. Estimate for 1975.	
Space	Concentrator radiation.		5 kw (estimate for future).		2 percent	7-10 percent (estimate for 1975).		2.5 watts/ft²	1w/lb with thermal storage.			Greater than 5 years (1975).		$25/kw. Estimate for 1975. Estimate $1,500/ton (for 1965).	Not a
Cooling. Heat pumps (submarine air conditioning).	DC electrical power	Heat	Refrigerator, 8,500 Btu/hr 0° F-55° F. Air conditioner, 9 ton.	Stages 2, 3, 4, 5	COP=2		Must reduce cost. Must optimize thermoelement length, packing density, and overall heat transfer coefficient between thermoelectric junctions and hot and cold fluids.		Estimated 200 lb/ton air conditioning.		2,000 hour (no degradation). 1,300 hour (1 percent degradation).		Approximately $2,250/ton air conditioning.		
Direct generation of electrical power for special applications.	Heat and magnetic field.	DC electrical power.	Not established	Stages 1, 2	Not established	5 percent (projected estimate) 1.6 percent (theoretical estimate (B = 10 kilogauss 300° K.[20] 2-4 percent (theoretical estimate).[22]	Must have superconductivity magnet in order to make Nernst effect competitive from weight or economic standpoint.[22]	280kw/ft³ (theoretical estimate).[20]	5w/lb (projected estimate). 1.45-10w/lb [21 22] (theoretical estimate). Assumes superconducting magnet and neglects weight of heat source.		Not established		Not established		Not e
Heat pump for temperatures below room temperature. Will not compete with Peltier devices for above room temperatures.	DC electrical power and magnetic field.	Heat	do.	do.	do.						do.		do.		Not a

3

		Develop high power density space cell using alkali metals. Microbiology research to study potential of bio-chemical fuel cells. Develop corrosion-resistant materials for low temperature acid electrolyte cells. Develop materials for high temperature cells. Research to study: Heat trasfer. Mass trasfer. Catalyst recovery and regeneration. Fuel purification.				200-800 hours (laboratory tests).					
	65 percent maximum (estimate).										
						600 hours (laboratory tests).					
percent			10 kw/ft²	30							
						550 hours (laboratory tests).					
	Unknown										
rcent	Maximum 10 percent (estimated).				Potentially better than other con version methods with moving parts.		5-10 years (estimated).				Not established.
rcent		Theoretical studies aimed at determining relationships among fundamental parameters. Example: Electrical transport and lattice thermal transport. Study of materials (alloying, etc.) in a program which is consistant with the theory program. Study of the effects of inhomogeneities in thermoelectric materials with development of improved methods of detection, elimination, and possible exploration. Behavior of materials over larger temperature range. Corrosion of materials. Theoretical study to see if there is an upper limit to Z.						4-15 watt commercial device $30/watt (estimated).		Estimate based on $2-$3/kwh. $30/watt device amortized over 5-year period.	
percent				5 (Typ) (w/5 lb fuel).							
			150	8 (Typ) (Includes fuel for 8 hours.)							
rcent	8-11 percent (estimate for 1975).			10. Laboratory generator w/o isotope.		1 year, design. 2 year, minimum 2 year, design 2 year, life.	Greater than 5 years.		$25/kw. Estimate for 1975, does not include isotope.	$11.5/kwh (10 watt device). $1.15/kwh (1 kw device) (estimate for device currently under development).	
rcent (esti-e).	5-8 percent (estimate for 1975).			15.5-50 [19]. Combined generator, does not include reactor shielding.[19]			Greater than 5 years (1975).		$25/kw. Estimate for 1975.		
rcent	6-8 percent (estimate for 1975).		2 watts/ft²	15-20 w/o system deploy and support structure.		1 year (10 percent degradation, laboratory test). Poor in flight tests.	Greater than 5 years (1975).	Not established	$25/kw. Estimate for 1975.		
ent	7-10 percent (estimate for 1975).		2.5 watts/ft²	1w/lb with thermal storage.			Greater than 5 years (1975).		$25/kw. Estimate for 1975. Estimate $1,500/ton (for 1965).	Not applicable	Not applicable.
=2.		Must reduce cost. Must optimize thermoelement length, packing density, and overall heat transfer coefficient between thermoelectric junctions and hot and cold fluids.		Estimated 200 lb/ton air conditioning.		2,000 hour (no degradation). 1,300 hour (1 percent degradation).		Approximately $2,250/ton air conditioning.			
stablished	5 percent (projected estimate) 1.6 percent (theoretical estimate (B = 10 kilogauss 300° K.[20] 2-4 percent (theoretical estimate).[22]	Must have superconductivity magnet in order to make Nernst effect competitive from weight or economic standpoint.[22]	280kw/ft³ (theoretical estimate).[20]	5w/lb (projected estimate). 1.45-10w/lb [21] [22] (theoretical estimate). Assumes superconducting magnet and neglects weight of heat source.		Not established		Not established		Not established	Not established.
o.						do.		do.		Not applicable	Not applicable.

4

Table I - Continued —*Status of technologic development of energy devices* [1]

Name	Description of device: Primary application	Description of device: Resources input (form of energy)	Description of device: Type output (form of energy)	Description of device: Scaling range	State of technology: State of R&D or technology [2]	State of technology: Current engineering efficiency	State of technology: Possible engineering efficiency	State of technology: Limiting phenomena and required research	Performance: Specific power of device: Watts/ft [3] (except as noted)	Performance: Specific power of device: Watts/lb (except as noted)	Performance: Reliability	Performance: Present life	Performance: Future life
THERMIONICS	Direct generation of electric energy.	Noted below	Electrical DC, low voltage and high current.	Efficiency relatively independent of size.[23]	Stages 2 and 3	do		Develop technology of coupling converter with different types of available heat sources.[24] Investigate basic physics of the plasma diode. Research into optimization of emitter surface.[24] Reaction of cesium at emitter and collector surfaces and its effect on the work functions. Studies on the effect of composite emitter surfaces and crystal-oriented surfaces on emission. Study possibility of using additive materials in cesium vapor to aid in controlling space change.[24] Fundamental research on plasma properties of cesium. Effects of irradiation on nuclear fuels, electrode, structural, seal and insulator materials at temperatures associated with thermionic application. Development of new high-temperature nuclear coolant for use with out of pile thermionic systems. Development of stable, more efficient low-temperature diode. Develop high-temperature vacuum seals.			Depends on materials research. Potentially better than other conversion methods with moving parts.		
Chemical	Terrestrial	Fossil fuel, such as gasoline, kerosene, fuel oil, or natural gas.		0.01–5 kw (estimated).	Estimated that power supply may be tested in 1 year.		10–15 percent (estimated).[25]			1–200 [25] (estimated).		1,000 hours (estimated to be feasible with present materials).	1–5 years [25] (estimated).
Nuclear	Space	Radioisotopes		0.01–5 kw (estimated).[23] (SNAP-13 = 25 watts).	Stage 2 unit may be available in 2 years.		10–15 percent (estimated).[25]			1–200 [25] (estimated). (SNAP-13 3.3 including fuel.[24]			1–5 years [25] (estimated). (SNAP-13 designed for 130 days).
	Naval (submarine). Topping for nuclear powerplant.	Nuclear reactor		1 kw–10 Mw [24] (design objectives).			10–20 percent (estimated).[25]			2–200 [25] (estimated).			
Solar	Space. Underdeveloped countries.	Solar radiation		0.01–5 kw (estimated).[25]	Flight test in 2 to 3 years.		10–15 percent (estimated).[25]			1–200 [25] (estimated).			1–5 years [25] (estimated).
Electrical simulating heat source.		Electrically heated in laboratory.				5–16 percent (approximately).	15–33 percent [26]					200–8,538 hours	
		Nuclear heated in laboratory.				4–11.5 percent (estimated).	4–11 percent (estimated)					10–303 hours	
		Solar unit electrically heated in laboratory.				4–9 percent (measured).						50–1,000 hours	
SOLAR		Radiation											
Domestic	Heating	do			Stage 4						Potentially good		
	Cooling (air conditioning)	do			Stage 2								
Industrial	Refrigeration	do			Stage 1								
	Desalting	do			Stage 3				0.1 gal/ft [3]				
Direct: Photovoltaic	Auxiliary power generation at low power levels for industrial use, space use, communications, fuel-poor countries.	do	Electrical DC	0.1–1 kw [19]	Stage 5			Research and development toward simplification and cost reduction. Investigate physical and electrical properties of materials (such as purification and crystal growth) and obtain fundamental electrical data on single crystals. Develop solar cell which is less sensitive to elevated temperatures. Learn how to fabricate optically precise yet light weight solar collectors.					
Silicon		do	do			Approximately 15 percent.			13.35	45 [27] (typical)			
Thin film		do	do			About ⅙ that of single-crystal cells.				14.3 [27] (typical)			
Photochemical		do	Chemical		Stage 2	Values as high as 30 to 70 percent have been reported in the laboratory.[28]							
Thermionic	Space	do	Electrical DC	0.01–10 kw [19]	Stage 3	4–9 percent	Estimated 20 percent.			10 9–16.5 [19]		50–1,000 hrs. (laboratory tests of flight weight convertor.)	
Thermoelectric		do	do		Stage 4								
Flat Plate		do	do	0.1–10 kw (estimate for future).	Flight tested	1.5 percent	6–8 percent (estimate for 1975).		2	1–17	Poor at present	Poor	Greater than 5 years (1975).
Concentrator		do	do	5 kw (estimate for future).		2 percent	7–10 percent estimate for 1975).		2.5		Fair at present	Approximately 1,000 hours.	do
Turbo generator		do	Electrical AC		Stage 4								
Hg Rankine Cycle	Space	do	do	3–20 kw			Estimate 10 percent total system.			4–5.5		2,500 hours	

1 Unless otherwise noted data was obtained from solicited review papers and panel discussions held exclusively for the purpose of this study.
2 Numbers in this column refer to status of research and development.
Stage 1. Fundamental applied research.
Stage 2. Construction of a laboratory model.
Stage 3. Construction of a pilot device.
Stage 4. Construction of an industrial prototype.
Stage 5. Research for improvement and perfection.
3 Private communication. Cmdr. F. J. Sisk, USN, Bureau of Ships.
4 Brown, J. J. William. Some Aspects of MHD Power Plant Economics. Pres. at 3d Symposium on Engineering Aspects of MHD, University of Rochester, Mar. 28-29, 1962.
5 Estimate based on fuel cost of 15 cents/million Btu.
6 Estimate based on fuel cost of 30 cents/million Btu.
7 Mills/kilowatt data based on an assumed 13¼ percent annual fixed charge rate.
8 AEC Report to the President. Civilian Nuclear Power, 1962.
9 Lewiston plant, New York.
10 Grand Coulee plant, Washington.
11 Based on present day cost of single-purpose hydroelectric generating stations.
12 Minimum size for self-excitation appears to be of the order of 10 Mw gross output. This size would be markedly reduced if superconducting magnets can be developed.
13 Figures assume the availability of superconducting magnets. Work cited in footnote 4.
14 Efficiency is based on net output of MHD generator (subtracting power required for magnet) and gross heat input from the combustion chamber. Efficiencies of the MHD energy exchange (based on heat input and gross power output) as high as 40 percent have been achieved in the laboratory.
15 Estimate based on use of superconducting magnet.
16 Sutton, G., and P. Gloersen. Magnetohydrodynamic Power and Propulsion. Magnetohydrodynamics, ed. by A. B. Cambel, T. P. Anderson, and M. M. Slawsky. Northwestern University Press, 1961, p. 243.
17 Private communication, Richard J. Rosa.
18 Moffatt, W. C. Magnetohydrodynamic Power Generation. Its Principles and Problems. Project Squid, Tech. Rept. MIT-29-P, January 1963.
19 Wilson, Volney C. Electric Energy Sources and Conversion Techniques for Space Vehicles. IAS Paper No. 60-31, January 1960.
20 Angrist, S. W. A Nernst Effect Power Generator. ASME paper No. 62 HT-36.
21 Generator capable of 60-watt output.
22 Colwell
Atomic Re
23 Egli, P
24 Private
25 Approxi
26 Theoret
to 1,800° C.
27 Withou
28 Rosenb
version. U.

Table I - Continued —*Status of technologic development of energy devices* [1]

	Description of device				State of technology				Performance					Economics			
									Specific power of device					Capital costs		Power costs	
	Primary application	Resources input (form of energy)	Type output (form of energy)	Scaling range	State of R&D or technology [3]	Current engineering efficiency	Possible engineering efficiency	Limiting phenomena and required research	Watts/ft [2] (except as noted)	Watts/lb (except as noted)	Reliability	Present life	Future life	Present	Future	Present	Future
CS.	Direct generation of electric energy.	Noted below	Electrical DC, low voltage and high current.	Efficiency relatively independent of size.[23]	Stages 2 and 3	do		Develop technology of coupling converter with different types of available heat sources.[24] Investigate basic physics of the plasma diode. Research into optimization of emitter surface.[24] Reaction of cesium at emitter and collector surfaces and its effect on the work functions. Studies on the effect of composite emitter surfaces and crystal-oriented surfaces on emission. Study possibility of using additive materials in cesium vapor to aid in controlling space change.[24] Fundamental research on plasma properties of cesium. Effects of irradiation on nuclear fuels, electrode, structural, seal and insulator materials at temperatures associated with thermionic application. Development of new high-temperature nuclear coolant for use with out of pile thermionic systems. Development of stable, more efficient low-temperature diode. Develop high-temperature vacuum seals.			Depends on materials research. Potentially better than other conversion methods with moving parts.			Not established	$100/kw. Estimate based on large scale production of thermionic diode.[24]	Not established	Not established.
	Terrestrial	Fossil fuel, such as gasoline, kerosene, fuel oil, or natural gas.		0.01–5 kw (estimated).	Estimated that power supply may be tested in 1 year.		10–15 percent (estimated).[25]			1–200 [25] (estimated).		1,000 hours (estimated to be feasible with present materials).	1–5 years [25] (estimated).				
	Space	Radioisotopes		0.01–5 kw (estimated).[25] (SNAP-13=25 watts).	Stage 2 unit may be available in 2 years.		10–15 percent (estimated).[25]			1–200 [25] (estimated). (SNAP-13 3.3 including fuel.[24]			1–5 years [25] (estimated). (SNAP-13 designed for 130 days).				
	Naval (submarine). Topping for nuclear powerplant.	Nuclear reactor		1 kw–10 Mw [24] (design objectives).			10–20 percent (estimated).[23]			2–200 [25] (estimated).							
	Space. Underdeveloped countries.	Solar radiation		0.01–5 kw (estimated).[25]	Flight test in 2 to 3 years.		10–15 percent (estimated).[25]			1–200 [25] (estimated).			1–5 years [25] (estimated).				
mulat- ource.		Electrically heated in laboratory.				5–16 percent (approximately).	15–33 percent [26]					200–8,538 hours					
		Nuclear heated in laboratory.				4–11.5 percent (estimated).	4–11 percent (estimated)					10–303 hours					
		Solar unit electrically heated in laboratory.				4–9 percent (measured).						50–1,000 hours					
		Radiation									Potentially good					Not applicable	Not applicable.
	Heating	do			Stage 4												
	Cooling (air conditioning)	do			Stage 2												
	Refrigeration	do			Stage 1												
	Desalting	do			Stage 3				0.1 gal/ft [2]								
ltaic	Auxiliary power generation at low power levels for industrial use, space use, communications, fuel-poor countries.	do	Electrical DC	0.1–1 kw [19]	Stage 5					45 [27] (typical)							
on		do	do			Approximately 15 percent.		Research and development toward simplification and cost reduction. Investigate physical and electrical properties of materials (such as purification and crystal growth) and obtain fundamental electrical data on single crystals. Develop solar cell which is less sensitive to elevated temperatures. Learn how to fabricate optically precise yet light weight solar collectors.	13.35					$200–$400/w	Unlikely that cost can be reduced significantly. Automation could reduce price to $50/w maybe $1/w in far future.		
film		do	do			About ⅛ that of single-crystal cells.				14.3 [27] (typical)							
mical		do	Chemical		Stage 2	Values as high as 30 to 70 percent have been reported in the laboratory.[28]											
nic	Space	do	Electrical DC	0.01–10 kw[19]	Stage 3	4–9 percent	Estimated 20 percent.			10 9–16.5 [19]		50–1,000 hrs. (laboratory tests of flight weight convertor.)					
lectric		do	do		Stage 4												
Plate		do	do	0.1–10 kw (estimate for future).	Flight tested	1.5 percent	6–8 percent (estimate for 1975).		2	1–17	Poor at present	Poor	Greater than 5 years (1975).	Not established	$25 (estimate for 1975)	Not established	Not established.
en- tor.		do	do	5 kw (estimate for future).		2 percent	7–10 percent estimate for 1975).		2.5		Fair at present	Approximately 1,000 hours.	do		do	do	Do.
n-		do	Electrical AC		Stage 4												
ankine cle.	Space	do	do	3–20 kw			Estimate 10 percent total system.			4–5.5		2,500 hours		$875/kw chlorobenzene turbine in Israel.			

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Villiam. Some Aspects of MHD Power Plant Economics. Pres. at 3d
ngineering Aspects of MHD, University of Rochester, Mar. 28–29, 1962.
d on fuel cost of 15 cents/million Btu.

[6] Estimate based on fuel cost of 30 cents/million Btu.
[7] Mills/kilowatt data based on an assumed 13½ percent annual fixed charge rate.
[8] AEC Report to the President. Civilian Nuclear Power, 1962.
[9] Lewiston plant, New York.
[10] Grand Coulee plant, Washington.
[11] Based on present day cost of single-purpose hydroelectric generating stations.
[12] Minimum size for self-excitation appears to be of the order of 10 Mw gross output. This size would be markedly reduced if superconducting magnets can be developed.
[13] Figures assume the availability of superconducting magnets. Work cited in footnote 4.
[14] Efficiency is based on net output of MHD generator (subtracting power required for magnet) and gross heat input from the combustion chamber. Efficiencies of the MHD energy exchange (based on heat input and gross power output) as high as 40 percent have been achieved in the laboratory.
[15] Estimate based on use of superconducting magnet.
[16] Sutton, G., and P. Gloersen. Magnetohydrodynamic Power and Propulsion. Magnetohydrodynamics, ed. by A. B. Cambel, T. P. Anderson, and M. M. Slawsky. Northwestern University Press, 1961, p. 243.
[17] Private communication, Richard J. Rosa.
[18] Moffatt, W. C. Magnetohydromagnetic Power Generation. Its Principles and Problems. Project Squid, Tech. Rept. MIT-29-P, January 1963.
[19] Wilson, Volney C. Electric Energy Sources and Conversion Techniques for Space Vehicles. IAS Paper No. 60-31, January 1960.
[20] Angrist, S. W. A Nernst Effect Power Generator. ASME paper No. 62-HT-36.
[21] Generator capable of 60-watt output.
[22] Colwell, J., G. Guthrie, and R. Palmer. Static Energy Conversion Studies. General Atomic Rept. No. 4088, April 1963.
[23] Egli, Paul H. Direct Energy Conversion. Naval Res. Rev., May 1960.
[24] Private communication, George N. Hatsopoulos.
[25] Approximate goal of current research.
[26] Theoretical estimate for maximum possible efficiencies at emitter temperatures of 1,200° to 1,800° C.
[27] Without erecting structure.
[28] Rosenberg, Norman. Photochemical Processes and Their Utilization for Energy Conversion. U.S. Government Research Report PB 151461, v. 1, November 1958.

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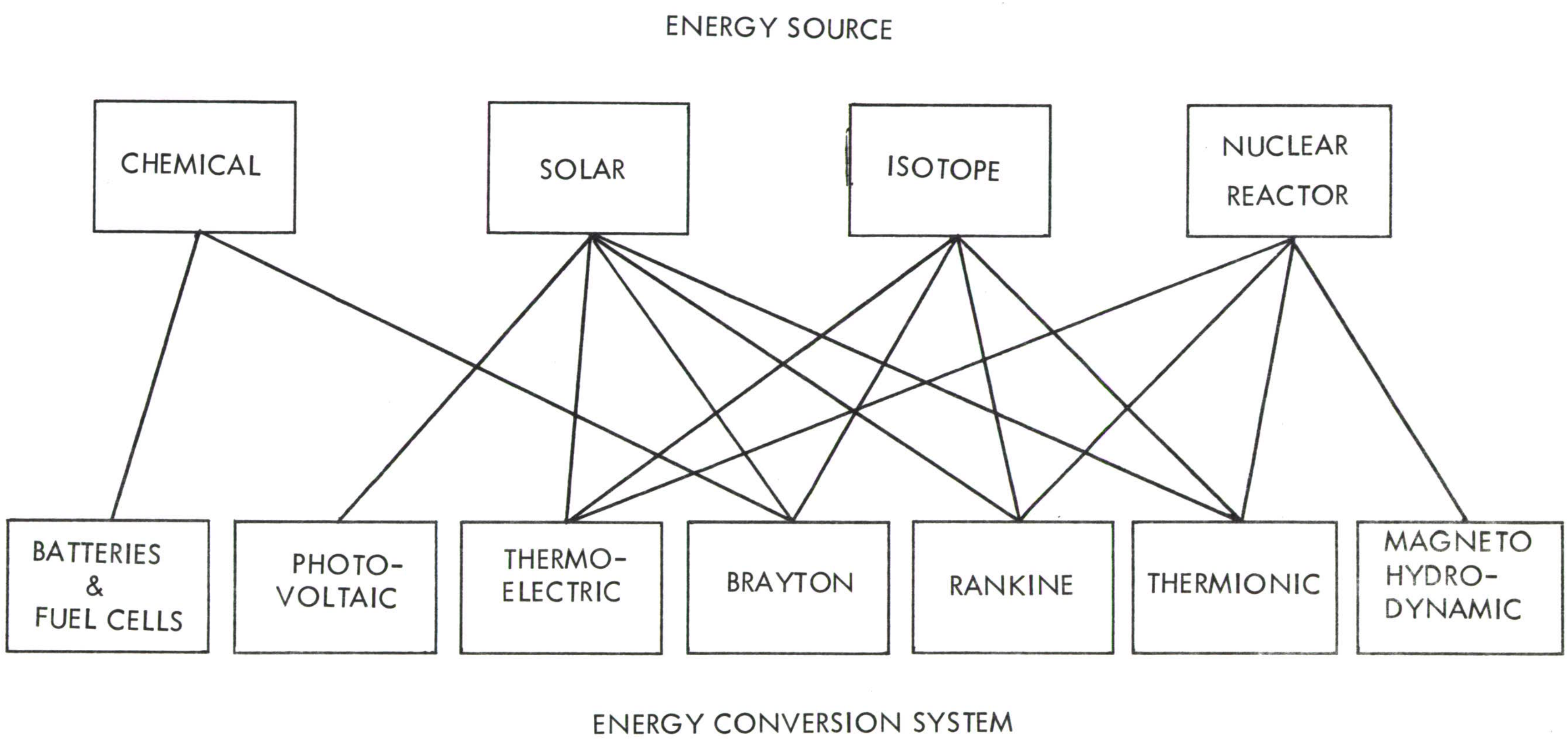

FIGURE 1 CANDIDATE POWER SOURCES FOR SMALL UNATTENDED APPLICATIONS

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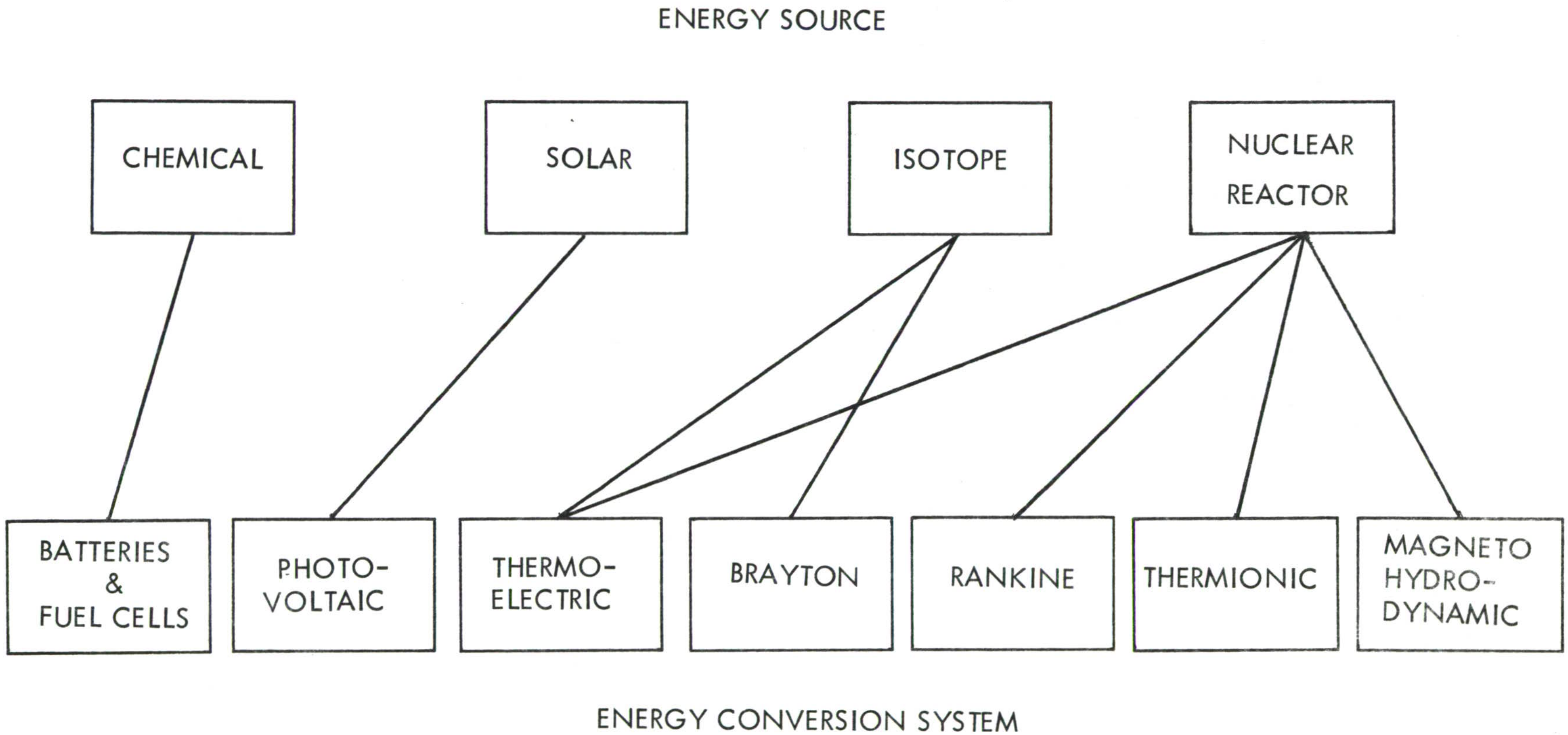

FIGURE 2 POWER SOURCES SELECTED BY NASA FOR FURTHER DEVELOPMENT

In a different environmental context, a report[4] by the National Academy of Sciences concludes that two basic types of energy systems in the 1-100 kW range are available to meet current naval undersea needs. These are underwater power cable systems and conventional, aqueous electrolyte batteries. The report further concludes that two additional basic types of energy systems are now sufficiently advanced to meet naval undersea needs in the short-run, 5-to 10-year time frame. These are hydrogen-oxygen fuel cells and heat-dynamic converters. In the long run, the National Academy believes that isotope-fueled systems employing static or dynamic converters, small nuclear reactors, and high-performance primary and secondary electrochemical systems have promise for meeting naval undersea requirements.

The foregoing broad overview of current thinking is intended to illustrate that the present state of technological development has not revealed a single preferred power source, or even a few, to which development support should be directed, even though many agencies are directing their efforts toward specific requirements. This conclusion is supported by a current survey[5] by the U.S. Army Mobility Equipment Research and Development Command (USAMERDC). Their report states:

> "A similar survey made by USAMERDC in 1965 found that there was insufficient factual data available to reach a completely definitive conclusion. It was hoped that the technological advances in the intervening three years would have yielded the necessary data. Although this was found true to a certain extent, there were still several projections that had to be made in the present study, especially in the area of life and cost."

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4 / Energy Systems of Extended Endurance in the 1-100 kW Range for Naval Undersea Applications, a Report by the Power of Energy Sources of the Committee on Undersea Warfare, National Academy of Science-National Research Council, September 1968.

5 / Special Study on Silent Electric Power Generators for Tactical Applications, Electrotechnology Laboratory, U.S. Army Mobility Equipment Research and Development Command, August 1968.

The brief survey which Booz-Allen Applied Research has conducted under the present study confirms that there are numerous theoretical papers on candidate sources and that there is a paucity of test data on actual conversion devices. While there are a number of industrial firms interested in the subject area, the state-of-the-art and the small market have combined to limit their efforts to the production of no more than a few prototype devices, usually under the auspices of a Government-sponsored research and development contract.

II. A REFERENCE BASELINE CONFIGURATION

The USAMERDC study contains a comprehensive comparative analysis of 0.5-to 15-kW power sources which are considered to be candidate systems for development in the short and intermediate time frame. In addition, these candidate systems are compared with the present general purpose, military standard (MILSTD) family of reciprocating engine generator sets.

Army experience with its MILSTD sets is extensive and has revealed them to possess many favorable characteristics except for silence. Evaluation by USAMERDC of the MILSTD sets included consideration of silencing measures.

The choice of the MILSTD sets as a reference base seems appropriate, and they are so used in this report. Performance parameters for these units are well-established and documented. Such data provides a firm point of departure for assessment of candidate developmental systems where performance is less well-demonstrated. Data for these units, in a silenced configuration as developed by USAMERDC, are shown in Table 2.

TABLE 2
SILENCED MIL-STD ENGINE GENERATOR SETS
MAJOR TECHNICAL CHARACTERISTICS

Rating (kW)		0.5	1.5	3.0	5.0	10.0
Weight (lb.)	STD	70	125	285	488	850
	Silenced	165	300	885	1450	2200
Volume ($ft.^3$)	STD	3.2	6.0	12.1	17.3	28.0
	Silenced	10.7	11.0	22.1	33.6	60.5

Fuel Type	MIL-G-3056 MIL-F-5572
Ambient Temperature Range	-65° to +125°F
Altitude	Rated Output at 5000 ft, 107°F 90% Rated Output at 8000 ft, 95°F
Time Between Overhaul	1500 hours
Audibility	Inaudible at distances over 100 meters vs. HEL Jungle Ambient Noise Background

III. CANDIDATE POWER SOURCES

We have attempted, albeit in limited depth, to review the current performance status and potential of a wide array of energy conversion devices. Our analysis included collection and review of published reports and telephone contact with a number of government agencies and industrial firms. The results of this effort are summarized in the material that follows.

1. ELECTROCHEMICAL POWER SOURCES[6]

This section reviews the state-of-the-art of electrochemical power sources which are considered pertinent to this study. Data is presented on batteries, fuel cells, and thermoelectric devices.

(1) Conventional Batteries[7]

Conventional batteries have a number of operating advantages. They have no moving parts, thus are capable of silent operation. They can be operated over a wide range of ambient conditions and operate at relatively low temperatures. They have a high reliability. Failure usually occurs one cell at a time in such a way that operation can be extended with degraded output for some period of time. Both primary (nonregenerable) and secondary (regenerable) cells are readily available in a wide variety of types, sizes, and configurations.

Conventional batteries, however, have a number of distinct disadvantages. Their energy densities and specific energies are low compared with other energy sources and conversion systems. They usually provide only a few watts per pound and a few kilowatts per cubic foot. Their operating power levels are limited by internal electrode, electrolyte, and separator losses, and these losses increase rapidly with load. The features of various primary and secondary cells now available are summarized in Tables 3 and 4.

6/ Prospects for Electric Vehicles, A Study of Low-Pollution-Potential Vehicles - Electric, Department of Health, Education and Welfare, National Center for Air Pollution Control, Arthur D. Little, Inc., May 1968.

7/ NAS-NRC report, op. cit.

Table 3

SUMMARY OF PRIMARY BATTERY CHARACTERISTICS[a]

Type	Anode	Cathode	Electrolyte	Temp. °F	Open circuit voltage (V)	Typical Operating voltage (V)	Theoretical energy[b] density (Wh/lb)	Actual energy density (Wh/lb)	Actual energy density (Wh/in.^{3})	Maximum power density[e] (W/lb)	Maximum power density[e] (W/in.^{3})	Cost[f] ($/kWh)	Operating Life	Remarks
Conventional														
Leclanche'	Zn(Hg)	MnO_2(C)	$NH_4Cl-ZnCl_2$	20-140	1.6	0.9-1.5	155	20-60	1.6-5.0	3	0.2	20-30	36 mo	conventional dry cell; sloping discharge curve
Mercury (Rubin)	Zn(Hg)	HgO(C)	KOH-ZnO	0-140	1.35	1.2-1.3	115	40-75	3-7	5	0.6	130	36-48 mo	constant voltage during discharge; heavier drains, higher capacity than Leclanche' cells
Akaline manganese dioxide	Zn(Hg)	MnO_2 (C)	KOH	-40-140	1.52	0.9-1.5	185	30-75	3-5	5	0.4	50	36 mo	heavier drain rates than Leclanche'; sloping discharge curve
Air Cell	Zn(Hg)	O_2 (C)	KOH	20-120	1.36	1.1-1.2	435[e]	40-100[c]	2-6[c]	-	--	80	30[d] mo	utilizes O_2 from air
Silver-zinc	Zn	AgO	KOH	0-140	1.8	1.3-1.6	205	40-70	5-7	6	1.0	240	24-36 mo	Also available as reserve and secondary cells
Magnesium dry cell	Mg	MnO_2(C)	$Mg(ClO_4)_2$	0-140	2.0	1.3-1.7	240	25-75	1.9-4.5	20	1.2	40	12-24 mo	higher capacity than Leclanche'; 35-40% of Mg consumed by corrosion producing H_2 during discharge
Lalande	Zn(Hg)	CuO	NaOH	10-120	1.06	0.8-1.0	170	12-15	0.6-0.75	-	--	80	30 mo	low operating voltage; used for railroad signals
Reserve types														
Silver-zinc	Zn	AgO	KOH	0-180	1.8	1.3-1.5	205	30-70	2-7	300	12	240	24 hr-2 mo	very high drain rates; activated by introduction of electrolyte
Magnesium-silver chloride (seawater battery)	Mg	AgCl	$MgCl_2$+ sea water	20-100	1.6	1.0-1.5	120	20-30	1.3-1.8	-	--	290	0.1-80 hr	high drain rates; activated by introduction of water; used for torpedoes

Table 3 (Cont'd)

Magnesium-cuprous chloride	Mg	Cu_2Cl	$MgCl_2$ + sea water	20-100	1.4	1.0-1.3	150	15-20	0.7-1.0	-	--	---	0.1-50 hr	high drain rates; activated by introduction of water; less expensive than Mg-AgCl cell
Zinc-chlorine	Zn	$Cl_2(C)$	$ZnCl_2$, NH_4Cl	30-120	2.1	1.3-1.9	105	20-25	1.6-1.8	-	--	---	6 hr	high drain rates; other non-reserve-type worked on for torpedo and submarine applications in past
Thermal cells	Ca	$PbCrO_4$ (Ni)	LiCl, KCl fused	---	2.8	2.0-2.6	280	5-10	0.3-0.6	-	--	---	few mins.	high drain rate; activation by melting electrolyte
Ammonia activated	Mg	AgCl	KSCN, NH_3	-60-125	2.2	1.5-2.0	180	10-30	1-2	-	--	---	0.1-2 hr	high drain rate; activated by introduction of ammonia
Zinc-lead	Zn	PbO_2	H_2SO_4	0-140	2.5	2.0-2.3	---	20-26	---	-	--	---	several days	high drain rate; activated by introduction of electrolyte
Experimental types (non-reserve)														
Magnesium-organic depolarizer	Mg	m-dinitrobenzene	$MgBr_2$	0-130	1.65	0.9-1.3	250	40-80	2-4.5	-	--	---	>12 mo	one of the more promising of a number of cells using organic cathodic depolarizers
Aluminum dry cell	Al	MnO_2	$AlCl_3$, $(NH_4)_2Cr_2O_7$	---	1.7	1.0-1.6	---	---	---	-	--	---	---	higher capacity and voltage than Leclanche cell; wasteful corrosion of Al a problem
Magnesium bismuth oxide	Mg	Bi_2O_3	$MgBr_2$	---	1.6	1.0	---	---	---	-	--	---	---	surprisingly small drop off of voltage with time

[a] For the most part based on data from various battery manufactor's handbooks and ref. 2 and 3.
[b] Based on active components in cell.
[c] Does not include O_2 from air.
[d] After cell has been filled with electrolyte.
[e] Most cells have not been optimized for power density but rather energy density; in most instances maximum power density can be maintained only for a few minutes at a time.
[f] Estimated distributers or wholesale cost.

Table 4

SUMMARY OF SECONDARY BATTERY CHARACTERISTICS

Type	Anode	Cathode	Electrolyte	Temp. °F	Open circuit voltage (V)	Typical operating voltage (V)	Theoretical energy density (Wh/lb)	Actual energy density (Wh/lb)	Actual energy density (Wh/in.^{3})	Maximum power density (W/lb)	Maximum power density (W/in.^{3})	Cost[a] ($/kWh)	Operating Life	Typical no. of cycles	Remarks
Conventional															
Lead acid	Pb	PbO_2	H_2SO_4	-40-140	2.2	1.7-2.1	80-115	5-20	0.4-1.2	15-30	1-2	0.09(60)	2-14 yr	1500	conventional lead storage cell; presently used for submarines, automobiles, etc.
Edison	Fe	Ni oxides	KOH	-10-140	1.6	1.1-1.4	135	7-15	0.7-1.2	---	---	0.08(230)	6-20 yr	2000	much longer life than lead acid but lower capacity (Wh/lb) and more expensive
nickel-cadmium	Cd	Ni oxides	KOH	-40-140	1.35	1.0-1.3	105	12-15	0.7-1.0	15	1.5	0.21(700)	4-6 yr	1000-2000	available as completely sealed cell
silver-zinc	Zn	AgO	KOH,ZnO	0-140	1.8	1.3-1.6	205	30-80+	1.8-5.6	170	7.2	8.40(800)	6-18 mo	10-200	high capacity and very high drain rates; low cycle life; expensive
silver-cadmium	Cd	AgO	KOH	-10-140	1.4	1.0-1.3	120	16-33	1.4-3.0	---	---	2.50(950)	1-3 yr	300-500	greater number of cycles than silver zinc
alkaline manganese-zinc	Zn	MnO_2(C)	KOH	-40-140	1.5	1.1-1.4	185	20-30	2-3	6	0.4	--- (200)$_c$	1-3 yr	20-200	available as completely sealed cell; cycle life dependent strongly on depth of discharge
Experimental															
sodium-sulfur	Na	S	modified alumina	550	variable	1.5-2.0	350	150	8	---	---	---	---	---	laboratory stage
lithium-chloride	Li	Cl_2	fused chloride	450-650	4.1	3.5-4.0	1000	250	---	---	---	---	---	---	laboratory stage
lithium-chloride	Li	AgCl	$AlCl_3$,LiCl in propylene carbonate	<165	3.0	2.3-2.8	230	25-90	1.5-2.2	---	---	---	~1 yr	50-200	high cell voltage, still in laboratory stage
lithium-fluoride	Li	NiF_2	propylene carbonate	<165	3.0	2.5	750	100	---	---	---	---	---	---	high cell voltage still in laboratory stage

[a] First figure - cost per kWh of energy drawn from battery during anticipated cycle life; bracketted figure - initial cost.

The National Academy of Sciences considers that magnesium-silver-chloride primary cells and silver-zinc, lead-acid, silver-cadmium, and nickel-cadmium secondary cells are of interest for naval undersea applications. NASA has primary interest in silver-zinc, silver, cadmium, and nickel-cadmium secondary cells. The state of the art of some of these and similar devices is summarized in excellent fashion in the Arthur D. Little study.

(2) Fuel Cells

In a review[8] of government-sponsored fuel-cell research and development covering the period 1950-1964, John I. Thompson and Co. (NASA Contract No. NASW-1039) found that nearly 200 contracts had been awarded to 90 contractors up to December 1963. This effort had resulted in the publication of nearly 800 reports describing the work performed. Since the date of the report, fuel-cell research and development has continued to expand and fuel-cell technology has continued to advance. The state of the art is still evolving rapidly and, though some devices have advanced sufficiently for application, selection of a particular system remains a difficult and risky problem. The advantages, disadvantages, and potential of specific approaches and devices are still subject to a wide range of interpretation.

The Energy Study Group, in its survey[9] of the state of the art in fuel-cell research and development, concluded that only two classes of these devices were sufficiently advanced to justify a development effort. These were hydrogen and sodium amalgam cells, but the sodium amalgam cell was considered economically attractive only for special applications. The study further concluded that the only other type of cell for which development might be considered is the dissolved-fuel type, such as methanol. However, it was felt that development of the dissolved-fuel type should be postponed in deference to determination of the potential of some of the hydrocarbon cells.

8/ Fuel Cells, A Review of Government-Sponsored Research, 1950-1964, National Aeronautics and Space Administration, NASA SP-120, 1967.

9/ Interdepartmental Energy Study, op. cit.

The USAMERDC study reports upon their analysis of three different fuel-cell systems: (1) low-temperature alkaline electrolyte, (2) low-temperature acid electrolyte, and (3) high-temperature molten carbonate electrolyte systems. All of these are, of course, indirect systems in that hydrogen is extracted from the basic fuel for use in the fuel cell. Their selection for evaluation is based, among other things, upon the opinion that direct systems are not sufficiently advanced for reasonable projection of their ultimate performance characteristics.

Prototypes of catalytic, steam-reforming hydrogen generators for each of the three systems have been operated by USAMERDC, thus providing data for comparative evaluation purposes. Partial oxidation and thermal-cracking devices were not considered because of their low efficiency, but the report indicates that an intensive research program to combine the best qualities of all the fuel-conditioning methods is in effect.

USAMERDC considers the low-temperature alkaline system to be the most advanced, though most complex, of the three systems evaluated. The major problem with this process lies in obtaining a fuel acceptable to the alkaline electrolyte. To accomplish this, the course taken by the majority of alkaline fuel-cell developers is as shown in Figure 3.

The low-temperature acid system is considered to be less complex than the alkaline system and the acid system, employing a phosphoric acid electrolyte, is preferred by USAMERDC over the alkaline cell from an operational point-of-view. The acid cell, however, has severe materials problems. High loadings of a precious metal catalyst are required to achieve reasonable performance, resulting in a more expensive device.

The least complex of the three systems, and potentially the most efficient in large sizes (over 10 kW), is the high temperature molten carbonate system. The high operating temperature and the corrosive nature of the molten salt pose material problems, however.

In the views[10] of still another analyst, the hydrogen-oxygen, hydrazine-oxygen, and sodium-amalgam-oxygen systems are considered to be the only systems that have advanced to the state where

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10/ "Fuel Cells: Their Status and Future Outlooks," E. Yeager, Chemical Engineering Progress, September 1968.

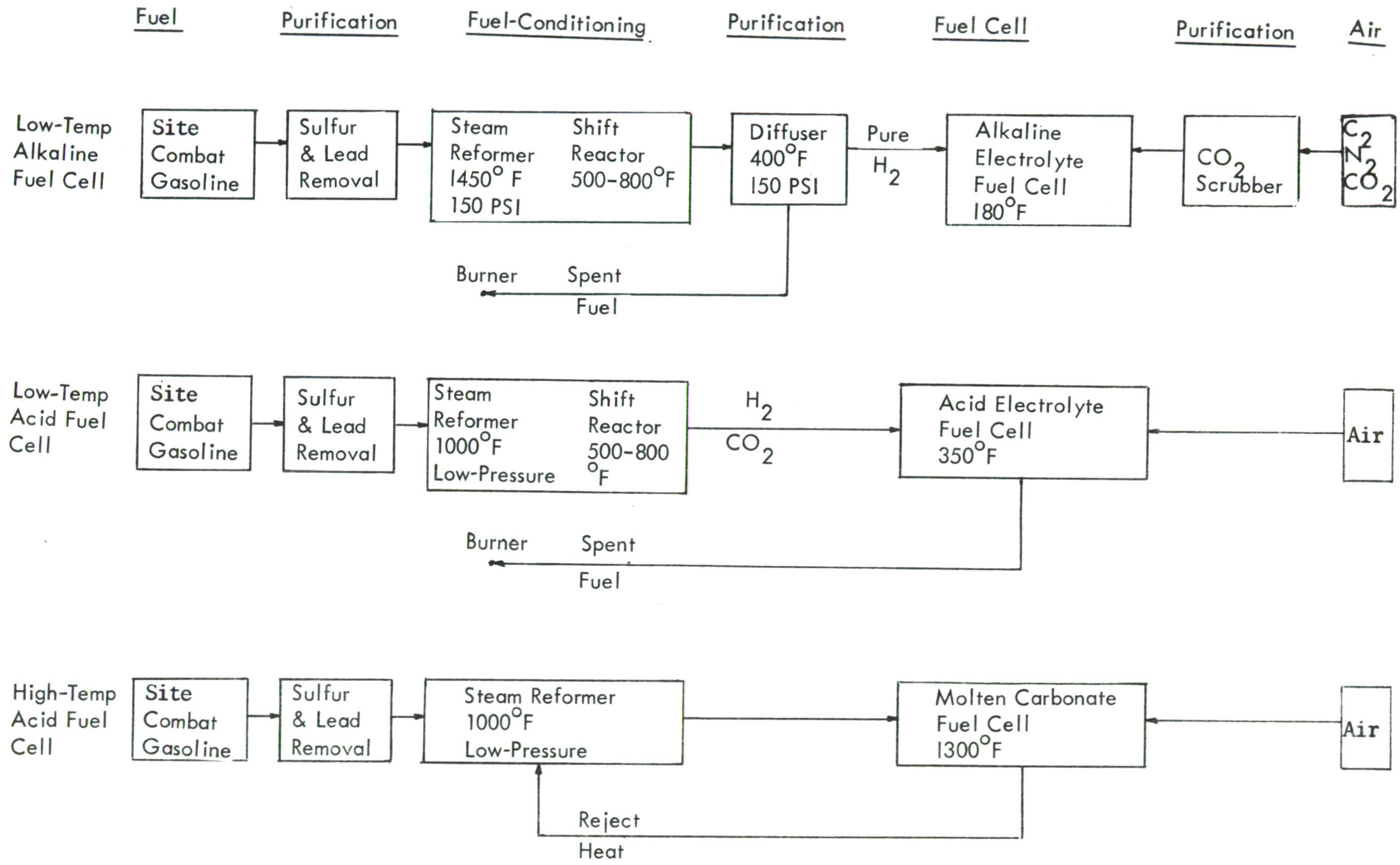

FIGURE 3 Simplified Flow-Charts of Fuel-Cell Systems

they are ready for application. Status of typical cells, as presented by this analyst, is shown in Tables 5 and 6. From the foregoing, there appears to be some consensus as to the current status and potential of fuel-cell systems, at least relative to broad classes of systems.

The hydrogen-oxygen cells of Union Carbide, Pratt-Whitney, and Allis-Chalmers, shown in Table 5, operate with strongly alkaline electrolyte. These are typical of the low temperature alkaline cell class considered by USAMERDC and other analysts. This class of device requires a purifier which, as reported by USAMERDC, has an investment cost on the order of $500 to $700 per kilowatt of fuel cell. Cost reductions of the order of 50 percent are thought to be possible in the long-run.

The General Electric cell shown in Table 6 uses an ion exchange membrane which is equivalent to an acid electrolyte. Systems of this class generally have high catalyst costs and require expensive current collectors. USAMERDC estimates that such costs should be reduced by 50 percent in the short-run (2-5 years) by improvements in power density, reduction of catalyst loading, and development of less expensive current collectors.

Table 7[11] illustrates the performance achieved by typical fuel cells which have been produced by each of the foregoing manufacturers. The units shown range in power output from about 50 watts to 2 kilowatts.

The hydrazine-oxygen cells of Union Carbide (see Table 6) use carbon electrodes containing catalysts while the cells of Monsanto and Allis-Chalmers use porous metal electrodes. The electrolyte in each case is a concentrated caustic (sodium or potassium). The cost of hydrazine is a constraint upon utilization of this type of cell.

The sodium-amalgam-oxygen cell of Table 7 provides a high cell voltage with power densities and volumes comparable to, or better than, hydrogen-oxygen cells. The cell operates efficiently on air without a necessity for carbon dioxide removal. Its principal disadvantage is the cost of sodium, which makes its power output rather expensive.

11/ 1967 NASA/JITCO Study, op. cit.

TABLE 5

TYPICAL FUEL-CELL SYSTEMS: HYDROGEN-OXYGEN

Systems	Electrodes	Electrolyte	Temp. °C	Remarks
A. U. S				
Union Carbide	C + catalysts	KOH	20-65	Low cost for catalysts.
Pratt-Whitney	Ni + catalysts	KOH	180-240	Project Apollo.
General Electric	Pt	ion membrane	20-80	Project Gemini; high cost for Pt catalysts.
Allis-Chalmers	porous metals + catalysts	KOH	20-95	Electrolyte in porous mat., spec. water control-removal sys.
B. Foreign				
Raney, nickel (Varta, USSR, Siemens, Brown-Boveri)	Raney nickel anode, usually silver or silver alloy cathode	KOH	20-90	Not as advanced as U.S. counterparts.
Quadrus (ASEA, Sweden)	Ni + catalysts	KOH	20-100	Submarine applic. antic.; 200 kW unit under const.
Tokyo Shibaura	Pd diffuser anode, Ni + catalysts cathode	KOH	30-100	Not as advanced as U.S. counterpart.

Typical operating voltages for hydrogen-oxygen cells listed are 0.75-0.90 V. Hydrogen and oxygen requirements are 0.087 to 0.105 lb/kWH and 0.70 to 0.84 lb/kWH, respectively, depending on the operating voltage.

TABLE 6

TYPICAL FUEL-CELL SYSTEMS OTHER THAN HYDROGEN-OXYGEN

System	Electrodes	Electrolyte	Temp. °C	Typical oper. voltage	lb./kWH anode	lb./kWH cathode	State of development, Remarks
Hydrazine-oxygen[1]	Porous metals, carbon + catalysts	KOH	20-70	0.85	1.25	0.75	Advanced: Union Carbide, Monsanto Allis-Chalmers.
Sodium amalgam-oxygen	Steel anode; carbon + catalysts cathode	NaOH	20-70	1.50	1.22	0.43	Advanced: Kellogg, Yuasa, Japan Storage Battery.
Hydrocarbon-oxygen[2]							
a. Pd diffuser anode	Pd diaphragm anode; Ni + catalysts cathode	NaOH	250	0.80	0.22	0.80	Early: Pratt-Whitney.
b. Phosphoric acid	Pt or Pt alloys	Phosphoric acid	150-200	0.30	0.59	2.10	Early: General Electric, ESSO, others.
c. Fused carbonate	Porous metals + catalysts	Fused carbonates	500-650	0.70	0.25	0.91	Intermediate: Texas Instruments, Institute of Gas Technology.
d. Ionic conducting solid	Pt	Yttrium zirconate	800-1000	0.70	0.25	0.91	Early: Westinghouse.
Alcohol-oxygen	Pt or Pt alloys	Phosphor acid	50-80°C	0.80	0.22	0.80	Early, ESSO, others.

[1]Hydrazine stored as a 60%-by-weight aqueous solution. [2]Assuming butane or a higher saturated hydrocarbon.

TABLE 7
PERFORMANCE OF H_2O_2 FUEL-CELL UNITS

Cell	Approximate electrode dimension, in.	Rated single-cell data		Unit power, watts	Weight, pounds	Life, hours
		A /sq ft	Volts			
Union Carbide:						
1961	6x6	40	0.8	560	. . .	150
1964	12x14	50	.8	[b] 320	. . .	>2600
General Electric IEM:						
Hope, 1962	7x10	15	.6	200	28	100
Gemini, 1965	7x8	40	.73	1000 (peak)	68	>400
Pratt & Whitney:						
1962	5 diam.	155	.87	280	. . .	>690
Apollo, 1965	. . . .	. . .	.87	1400 2300 (peak)	220	>500
Allis-Chalmers:						
1962	11x6½	85	.8	1500	. . .	3000
1965	4x7½	150	.75	[b] 45	14.5	. . . . . .

The molten carbonate cell is considered by USAMERDC to be the least expensive device of those evaluated. These high-temperature systems do not require a purifier or a precious metal catalyst. USAMERDC projects some additional cost reduction for these systems with advanced state-of-the-art.

(3) Biocells

Biocells are normally classified by the specific relationship of the biological microorganism to the process of electron transfer into indirect and direct categories. In the indirect cell, the microorganism catalyzes the formation of a fuel which is in turn used in a conventional fuel cell. In the direct cell, the substrate containing the microorganism acts as an electron acceptor or donor and is an integral part of the electrical circuit. The energy employed by the direct cell may derive from electromechanical metabolism, wherein electrons are shunted from the biological metabolic oxidation-reduction reactions to the external circuit, or from redundant energy normally shed by the microorganism in the form of heat, light, and chemicals.

Phenomena associated with biological fuel cells, or biocells, have been studied for years. Galvani, as early as 1771, investigated the reverse effect of an electric current on biological processes. Grove, who is considered by many to be the inventor of the conventional oxygen-hydrogen fuel cell, experimented with biological electricity in 1839.

In spite of an extended history, biocells have not progressed rapidly to a state of successful practical application. This slow rate of progress is due in part to the sensitivity of biocatalysts. They may be poisoned by changes in pH, temperature, or concentration. They must afford good electron transport among the electrolyte, substrate and electrodes. The mechanism of electron transport is the primary factor limiting development of biologically catalyzed fuel cells. The potential associated with conventional fuel cells has accelerated their development in recent years. This development will hasten the development of the biocell, in particular, the indirect biocell. Nevertheless, an extended and expensive development will be required before the potential may be transformed to practical application.

2. THERMOELECTRIC DEVICES

Thermoelectric devices provide direct conversion of heat to electromotive force by use of a heat source, heat sink, and dissimilar materials. The conversion process is complex, and includes five identified phenomena which take place simultaneously: the Seebeck effect, the Joule effect, the conduction of heat, the Peltier effect, and the Thompson effect.[12] Common materials consist of combinations of dissimilar metals, metal and semiconductor, and p-type and n-type semiconductors. The latter is illustrated in Figure 4. Thermoelectric devices are usually categorized by energy source and include carbonaceous or fossil-fuel-fired, isotope, solar and nuclear reactor generators. General characteristics of some of these devices are shown in Table 8.[13]

The materials currently used in thermoelectric devices are upper-temperature limited and accordingly achieve only low efficiencies. The best laboratory devices, operating at high temperatures, have efficiencies of roughly ten percent, while commercial units range downward to less than two percent efficiency.

(1) Fossil-Fuel-Fired Thermoelectric Devices

Commercial thermoelectric devices have been available in small sizes since about 1957. In 1962 and 1963, natural gas or propane-fired generators with outputs of about four to 15 watts became commonplace, and operated successfully in field service. Applications have been diverse and include power for railway caboose radio and lights, cathodic protection for gas and petroleum wells, microwave relay stations, remote weather stations, and wire line repeaters. Life expectancy claims for these small units range upward to 10 years. However, available commercial units carry warranties of full-rated output power for about one year. This is attributable in part to lack of operational experience.

12/ Zemansky, Mark W., Heat and Thermodynamics, 4th Ed., McGraw-Hill Book Co., New York, 1957.

13/ "Interdepartmental Energy Study," op. cit.

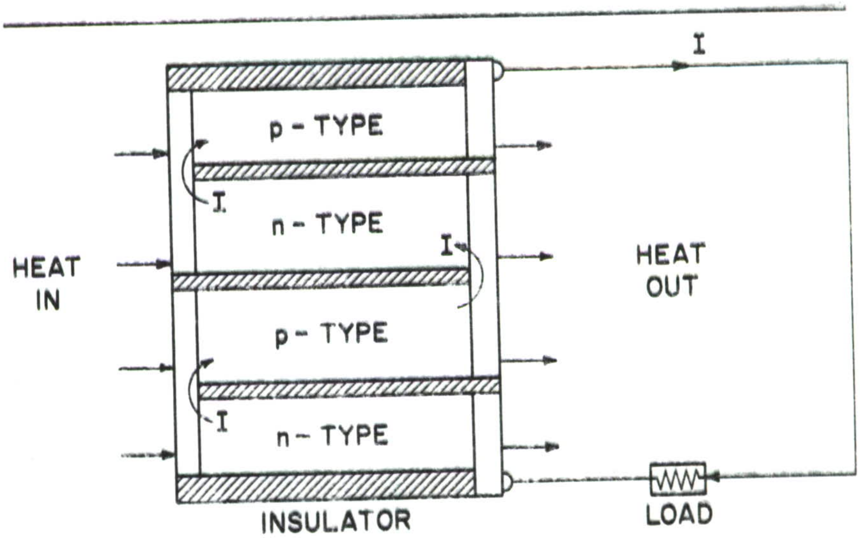

FIGURE 4 THERMOELECTRIC CONVERTER

TABLE 8
PARTIAL LIST OF THERMOELECTRIC GENERATORS

P_o (watts)	Temperature (nominal ° F)		Fuel	Duty	Efficiency (percent)	Remarks
	T_h	T_c				
2.5–3.5	620	115	Isotope Po^{210}	Continuous (space).	5.8	PbTe material in compression, weight 4 pounds, radiation cooled, SNAP III, January 1959.
3	400	100	Nuclear wastes.	Continuous (marine).	4.0	BiTe material, metallurgically bonded, water cooled.
2.5, 5, 10, 60	900	150	Radioisotope Sr^{90}.	Continuous	[1] 6.0	Includes SNAP-7 series PbTe n-type, p-type material.
4, 8, 15	1,000	[1] 400	Propane or natural gas.	Cyclic (marine and terrestrial).	1.6	80 to 100 watt-hours per pound fuel, natural convection cooled, $30 to $60 per watt.
10	400	180	Propane	do	2.0	BiTe material, metallurgically bonded, air cooled.
12	[1] 860	[1] 250	Hydrocarbon.	Continuous (terrestrial).	[1] .7	Cathodic protection use, air cooled, pressure hot junctions.
30	400	100	Propane	Cyclic (marine).	3.0	BiTe material, metallurgically bonded, water cooled, weight 40 pounds.
45	950	400	Leaded gasoline.	Cyclic (terrestrial).		PbTe n-type material, proprietary p-type material, forced convection cooled.
150	[1] 950	[1] 500	do	do		PbTe n-type material, PbSnTe p-type material.
267	850	280	Propane	do	1.4	Forced convection cooling, specific power = 7.5 watts per pound; burner heat flux = 8 watts per cm^2; pressure contacts, burner efficiency = 39 percent.
260	1,100	300	do	do	2.4	Specific power = 6.9 watts per pound; PbTe n-type material, and p-type material.
500	[1] 930	[1] 700	Nuclear	Continuous (space).	[1] 1.7	GeSi material, bonded junctions.
5,000	[1] 1,000	[1] 200	Hydrocarbon.	Cyclic (terrestrial).		

[1] Estimated values.

Since 1962, much larger devices have been produced, ranging upward to 200 and 500 watts. Units as large as 1.5 kilowatts have been proposed. Typical among such devices are those developed or under development by the Minnesota Mining and Manufacturing Company as shown in Table 9. Performance parameters claimed for some of these units are shown in Table 10.

The USAMERDC study discusses a number of thermoelectric device problem areas which have not been fully resolved. These include thermopile degradation (laboratory tests indicate power degradation of 20 to 25% per thousand operating hours); accessories; control instability; and visual, infrared, and aural signatures. Problems associated with accessories and control instability are due in part to the lack of experience in commercial applications. Problems associated with visual, infrared, and aural signatures are important only to applications in operating in a combat environment. The current status of operational hardware evaluated by USAMERDC indicates that systems with a useful life of more than 1,000 hours, including more than 100 start-stop cycles, can be built. However, evaluations have not extended to extremely cold ambient temperature operation and storage.

(2) Isotope Thermoelectric Generators[14]

Isotope-fueled thermoelectric generators have advantages which make them of interest in applications where long life and reliability are important. Table 11 presents some of the various devices of this nature which have been developed, primarily under the sponsorship of the Atomic Energy Commission.

The first series of these devices were the SNAP-3 (Systems for Nuclear Auxiliary Power) units.[15] The first four of these were Po-210-fueled demonstration units built in 1959. These demonstrated an overall efficiency of 5.8 percent, which is higher than could have been attained from

14/ Radioisotope-Fueled Thermoelectric Generators," F. Hittman and C.C. Silverstein, Engineering Developments in Energy Conversion International Conference on Energetics, The American Society of Mechanical Engineers, New York, 1965.

15/ Interdepartmental Energy Study, op. cit.

TABLE 9

3M THERMOELECTRIC DEVICE SUMMARY

Number	Device Name and General Description	Application	Heat Source	Watts
B-30	BASO Pilot Light Gas Solenoid Valve Control	Gas Appliances	Gas Flame	—
3M-3	Coast Guard Generator-Utilizes Basic 3M-1 Design Principles	Coast Guard Light	Propane	10
3M-4	Experimental High Power Generator	Signal Core Exp	Propane Burner	150
3M-5	"Man-Pack" High Power-to-Weight Field Power Supply	Navy-Marine Corp. Field Use	Propane Burner	250
3M-6	Light Weight, Compact Power Package	Terrestrial	Propane Burner	1.25
3M-7	Experimental "Flat-Plate" Generators; Forerunner of 3M Brand T/E 6	Experimental	Propane	2-15
3M-8	"Super Aztec", Cylindrical Array of B-30	Portable Power Use	Kerosene	1.5
3M-12	"Aztec" Array of Six B-30 Couples	Radios	Kerosene Lamp	0.15
3M-14	Lightweight Kerosene-Fueled Flat-Plate Generator	Portable Power Use	Kerosene Burner	30
3M-15	Flat-Plate Two-Watt 3M Brand Generator	Commercial	Propane Burner	2
3M-16	Model 505 3M Brand Commercial Thermoelectric Generator	Commercial	Propane Burner	4
3M-17	Model 510 3M Brand Commercial T/E Generator	Commercial	Propane Burner	8
3M-18	Model 515 3M Brand Commercial T/E Generator	Commercial	Propane Burner	15

TABLE 9 (CONTINUED)

Number	Device Name and General Discussion	Application	Heat Source	Watts
3M-19	Model 520 3M Brand Commercial T/E Generator	Commercial	Propane Burner	30
3M-20	Sixty-Watt 3M Brand Commercial T/E Generator	Commercial	Propane Burner	60
3M-21	Semi-automatic Battery-Charging System Utilizing 3M-19 Generator	Army Dugway Sampling Dev.	Propane Burner	30
3M-22	Developmental 200-Watt Generator	Experimental	Propane	200
3M-23	Lightweight Kerosene-Fueled Cylindrical Generator	Military Field Use	Kerosene Diesel Fuel Jet Fuel	100
3M-24	Two-hundred Watt 3M Brand Commercial Thermoelectric Generator	Commercial	Propane	200
3M-25	Lightweight Kerosene-Fueled Cylindrical Generator	Terrestrial	Kerosene, Diesel Fuel Jet Fuel	25
3M-26	Lightweight NAVY 300-Watt 35# Backpack	Terrestrial	Kerosene, Diesel Fuel Jet Fuel	300
3M-28	Lightweight 560-Watt Field Power Supply	Military Field Use	Kerosene, Diesel Fuel Jet Fuel	560
3M-29	Thirty-Watt Battery-Charging System Utilizing 3M-19 Generator	Coast Guard Battery Chg.	Propane	30
3M-2000	Thermoelectric Furnace (Bonded Flat-Plate)	Gas Furnace Contained Power	Natural Gas Flame	25

TABLE 10
SPECIFICATION CHART - THERMOELECTRIC GENERATORS

MODEL		ELECTRICAL CHARACTERISTICS				FUEL CONSUMPTION			PHYSICAL DATA		
Number	Description	Power[2]	Load[2] Voltage	Load[2] Current	Power[3] Range	Propane		Natural Gas	Weight	Dimensions	
		Watts	Volts	Amps	Watts	Lbs./Hr.	Gal./Hr.	Ft.³/Hr.	Lbs.		Inches
505	Thermoelectric Generator	9	1	9.0	8.5-10.0	.073	.017	1.23	28	A	12
	With 605-12 Converter-Limiter	5.3	12	.44	4.7-6.4					B	18
	With 605-24 Converter-Limiter	5.0	24	.21	4.4-6.0					C	12
										D	—
510	Thermoelectric Generator	15	2	7.5	14-18	.13	.023	1.9	31	A	12
	With 610-12 Converter-Limiter	11.2	12	.93	9.9-13.5					B	18
	With 610-24 Converter-Limiter	12	24	.50	10.6-14.2					C	12
										D	—
515	Thermoelectric Generator	28	3.8	7.3	26-32	.18	.042	3.5	50	A	12
	With 615-12 Converter-Limiter	20.5	12	1.7	18.5-24					B	18
	With 615-24 Converter-Limiter	21.5	24	.90	20-25					C	12
										D	30
520	Thermoelectric Generator	50	6	8.3	46-60	.30	.071	7.0	130	A	16[4]
	With 621-6 Limiter	50	6	8.3	46-60					B	21
	With 620-12 Converter-Limiter	41	12	3.4	36-50					C	18
	With 620-24 Converter-Limiter	43	24	1.8	38-52					D	38
530	Thermoelectric Generator	100	12	8.3	92-120	.60	.14	14.0	300	A	32
	With 631-12 Limiter	100	12	8.3	92-120					B	25
	With 630-24 Converter-Limiter	82	24	3.4	74-96					C	22.5
										D	36
540	Thermoelectric Generator					1.20	.28	28.0	700	A	58
	With 641-6 Limiter	200	6	33	188-240					B	24
	With 641-12 Limiter	200	12	16.5	188-240					C	20
	With 641-24 Limiter	200	24	8.3	188-240					D	36
	With 640-48 Converter-Limiter	163	48	3.4	147-192						

1. Fuel consumption may vary slightly depending upon air shutter adjustment.
2. Values are typical at 75° F. ambient temperatures, under a fixed matched load at constant gas pressure.
3. Typical power output range of generator for a variation in ambient temperature from +125° F. to -25° F.
4. Thirteen inches for generators without converter-limiter.

Warranty Power — Between ambient temperatures from -25° F. to 125° F., all generators are warranted to produce typical power within the following limits: Without converter-limiter, ±7% • With Limiter only, ±7% • With converter-limiter, ±15%

For typical power at various temperatures, see our "Power versus Ambient Temperature" curve. Copies of this curve can be obtained from 3M.

Limiter Adjustment — Voltage limiters are adjustable as follows:

Voltage Range	Model Numbers
13 - 15	605-12, 610-12, 615-12
13 - 18	620-12, 631-12
26.5 - 29.5	605-24, 610-24, 615-24
24 - 30	620-24, 630-24, 641-24

TABLE 11
SUMMARY OF SNAP DEVICES

Designation	Use	Power (watts)	Size* (inches)	Weight (pounds)	Isotope	Isotope's Half-life	Generator Life
SNAP-3	Demonstration device	2.5	4-3/4x5-1/2	4	Polonium-210	138 days	90 days
SNAP-3A	Satellite power	2.7	4-3/4x5-1/2	4.6	Plutonium-238	89.6 years	5 years
Undesignated	Axel Heiberg weather station	5	18x20	1680	Strontium-90	28 years	2 years minimum
SNAP-7A	Navigational buoy	10	20x21	1870	Strontium-90	28 years	2 years minimum
SNAP-7B	Fixed navigational light	60	22x34-1/2	4600	Strontium-90	28 years	2 years minimum
SNAP-7C	Weather station	10	20x21	1870	Strontium-90	28 years	2 years minimum
SNAP-7D	Floating weather station	60	22x34-1/2	4600	Strontium-90	28 years	2 years minimum
SNAP-7E	Ocean-bottom beacon	7.5	20x21	600	Strontium-90	28 years	2 years minimum
SNAP-7F	Offshore oil rig	60	22x34-1/2	4600	Strontium-90	28 years	2 years minimum
SNAP-9A	Satellite power	25	20x9-1/2	27	Plutonium-238	89.6 years	5 years
SNAP-13	Demonstration device	12	2-12x4	4	Curium-242	162 days	90 days
SNAP-15A	Military use	0.001	3x3	1	Plutonium-238	89.6 years	5 years
SNAP-19B	Nimbus-B weather satellite	30	22x10	30	Plutonium-238	89.6 years	5 years
SNAP-21	Deep sea use	10-20	18x44 max	644-1066	Strontium-90	28 years	5 years
SNAP-23A	Terrestrial uses	25-100	25x25	900	Strontium-90	28 years	10 years
SNAP-27	Lunar landings	60	18x18	30	Plutonium-238	89.6 years	5 years
SNAP-29	Various missions	500	–	500	Polonium-210	138 days	90 days

*Diameter times height.

a fossil-fueled device because of the elimination of stack-gas losses. Since 1959, a number of isotope-fueled devices have been developed not only for space but also for underwater and terrestrial applications.

The SNAP-7 series of generators are intended to evaluate the feasibility of Sr-90-heated devices for long-lived, buoy-based, underwater use or for remote terrestial applications. The weight of these units probably removes them from consideration for remote area applications. The SNAP-21, 23, 27, and 29 series of devices, however, may well warrant serious consideration. The SNAP-23 system is specifically oriented toward remote terrestrial application. Design goals for these units specified that the thermoelectric (TE) converter must produce 60 watts power output at 24 volts over a five-year lifetime. Following demonstration of successful SNAP-23 converters, the SNAP-23A program was initiated with a 10-year lifetime goal. In addition, conceptual designs for 25- and 100-watt converters were sought.

The SNAP-27 power supply, although intended for lunar exploration, is designed to provide 56 watts for a minimum of one year. This entire power package, including fuel capsule, weighs only 38 pounds. This light weight is due largely to extensive use of beryllium components.

Major problems associated with isotope-powered devices include economics, fuel availability, safety, and handling, as well as the problems of thermoelectric converters.

(3) Photovoltaic Devices

The production of an electromotive force by incidence of radiant energy, commonly light, upon the junction of two dissimilar materials, is termed the photovoltaic effect. Direct energy conversion from solar radiation has proved to be an effective technique for satellite power levels below 1 kW.

Until recently, silicon photovoltaic cells were the only practical solid-state device for this purpose. The more recently developed thermoelectric (TE) flat-plate solar generator, employing the p-n junction, is superior, with regard to cost, power, degradation of performance with operating time, and thermal cycling. A comparison of costs is as follows:

Comparison of Photovoltaic and TE Panel Arrays

	Photovoltaic	Present TE	Future TE
Cost ($/w)	450	135	30
Specific Power (w/lb)	6.0	7.5	12.5
Operating Temp. (^{o}K)	300^{o}-325^{o}	500^{o}-550^{o}	

In spite of space power utilization, experience with solar-powered devices is relatively limited. Test data indicate that TE device power performance degrades by about 25 percent in 1000-1200 hours of operation. Tests also indicate that open circuit electromotive force and internal resistance are unaffected by thermal cycling.

The high cost of solar arrays, coupled with the intermittent and variable nature of terrestrial solar energy, make photovoltaic devices unattractive for power generation in remote areas.

3. DYNAMIC POWER SOURCES

Dynamic converters have, historically, represented the primary energy conversion devices. The technology of these systems continues to evolve and they, along with fuel cells, may well constitute the systems of greatest potential for Limited War Laboratory exploitation.

(1) Rankine Cycle Engines

Rankine cycle engines are receiving current attention for application as energy conversion devices, both for small electric power sources and for automotive propulsion. Performance characteristics for prototype steam electric power sources developed by the Thermo Electron Corporation are illustrated in Tables 12, 13, and 14. The 100-and 300-watt units have been evaluated by MERDC, and the larger unit will be delivered for their evaluation. In addition, MERDC has operating experience with mercury and organic compound devices.

TABLE 12

100-WATT STEAM-ENGINE-DRIVEN GENERATOR SET

CHARACTERISTICS	ACTUAL PERFORMANCE PRESENT PROTOTYPE	PROJECTED PERFORMANCE NEXT GENERATION UNITS
Power Output		
a. Electrical	100 watts at 12 and 28 v, dc	120 watts
b. Engine Shaft	1/4 hp at 1800 rpm	0.3 hp at 1800 rpm
Weight	29 lbs	22 lbs
Size	16" x 16" x 12-1/2"	14" x 14" x 12"
Fuel		
a. Type	JP-4, CITE, Gasoline, JP-5, Kerosene, Naptha	JP-4, CITE, Gasoline JP-5, Kerosene, Naptha
b. Flow Rate	0.5 lb/hr	0.45 lb/hr
c. Capacity*	0.5 gallon	0.82 gallon
d. Operating Time between Refueling at Full Power**	7 hours	12 hours
e. Specific Fuel Consumption	2 lbs/BHP-hr	1.5 lbs/BHP-hr
Efficiency, Overall (Electrical Power Output/Fuel Flow Rate x Heating Value)	3.7%	5%
Life	100-300 hours	1000 hours
Sound Pressure Levels	Inaudible at 100 meters	Inaudible at 25 feet
Control System***	Parasitic Load - Principle Fully Developed	Same

*Can be readily connected to an external fuel supply.
**Operating time between refuelings is extended for operation at less than rates power output.
***Set uses standard military alternator, electrical controls, no engine governor.

TABLE 13

300-WATT STEAM-ENGINE-DRIVEN GENERATOR SET		
CHARACTERISTICS	PRESENT PROTOTYPE	PROJECTED PERFORMANCE NEXT GENERATION UNITS
Power Output		
a. Electrical	300 watts at 28 v, dc	300 watts, at 28 v, dc
b. Engine Shaft	2/3 hp at 1800 rpm	2/3 hp at 1800 rpm
Weight	42 lbs	29 lbs
Size	14" x 14" x 14"	Same
Fuel		
a. Type	JP-4, CITE, Gasoline, JP-5, Kerosene, Naptha	JP-4, CITE, Gasoline JP-5, Kerosene, Naptha
b. Flow Rate	~1.15 lbs/hr	0.8 lb/hr
c. Capacity*	1.5 gallons	1.5 gallons
d. Operating Time between Refueling at Full Power**	~8 hrs	12 hrs
e. Specific Fuel Consumption	1.62 lbs/BHP-hr	1.2 lbs/BHP-hr
Efficiency, Overall (Electrical Power Output/Fuel Flow Rate x Heating Value)	~5%	7.2%
Life	300 to 1000 hrs	1000 to 2500 hrs
Sound Pressure Levels	Inaudible at 100 meters	Inaudible at 50 feet
Control System***	Parasitic Load - Fully Developed	Same

*Can be readily connected to an external fuel supply.
**Operating time between refuelings is extended for operation at less than rated power output.
***Set uses standard military alternator, electrical controls, no engine governor.

TABLE 14

1.5-KW STEAM-ENGINE-DRIVEN GENERATOR SET		
CHARACTERISTICS	ACTUAL PERFORMANCE PRESENT PROTOTYPE	PROJECTED PERFORMANCE NEXT GENERATION UNITS
Power Output		
a. Electrical	1.5 kw at 28 v, dc	1.5 kw at 28 v, dc
b. Engine Shaft	3 hp at 3600 rpm	3 hp at 3600 rpm
Weight	120 lbs	Less than 100 lbs
Size	20" x 20" x 24" long	16" x 18" x 22" long
Fuel		
a. Type	JP-4, CITE, Gasoline, JP-5, Kerosene, Naptha	JP-4, CITE, Gasoline, JP-5, Kerosene, Naptha
b. Flow Rate	4.2 lbs/hr	2.95 lbs/hr
c. Capacity*	3 gallons	1.8 gallons
d. Operating Time between Refueling at Full Power**	4.5 hrs	4 hrs
e. Specific Fuel Consumption	1.40 lbs/BHP-hr	0.95 lb/BHP-hr
Efficiency, Overall (Electrical Power Output/Fuel Flow Rate x Heating Value)	6.5%	9.3%
Life	To be determined	Greater than 1000 hrs
Sound Pressure Levels	To be determined	Inaudible at 100 meters
Control System***	Fully automatic operation; simple start-up in 1-2 minutes	Fully automatic operation; simple start-up in 1-2 minutes

*Can be readily connected to an external fuel supply.
**Operating time between refuelings is extended for operation at less than rated power output.
***Set uses standard military alternator, electrical controls, no engine governor.

Data[16] on several automotive steam engines either built or studied since 1950 are shown in Table 15. The engines shown are semi-closed-cycle systems requiring some make-up water, and all are piston-type expanders. Lubrication is accomplished with conventional hydrocarbon oils. The automotive engine data is of interest to the Limited War Laboratory only because improved technology that may be developed for these larger devices may have application in smaller power output ranges.

The use of steam as a working fluid is of interest because it is widely available and its characteristics are fairly attractive for use in Rankine cycle systems. It is, however, a poor lubricant and is not compatible with conventional hydrocarbon oil lubricants. Mercury, as a working fluid, has a high allowable temperature and is a relatively good lubricant. It has the disadvantages of toxicity and incompatibility with many metals, as well as limited availability. Organic fluids have relatively high specific volume and are compatible with most conventional metals. Organic fluids are, however, subject to chemical decomposition at high temperatures.

The operating experience of MERDC has confirmed most of the fluid problem areas indicated above. In addition, control of engine speed presents difficulties that have not been resolved. Seals, particularly for steam systems, present a continuing problem.

(2) Brayton Cycle Devices

Operational Brayton cycle machines in the small power ranges of interest to the Limited War Laboratory have not been developed. While the technology is well-known and projections of output down to low levels have been made, the basic technical problems with these systems in small sizes will likely exclude them from consideration in the foreseeable future.

16/ Study of Unconventional Thermal, Mechanical, and Nuclear Low-Pollution-Potential Power Sources for Urban Vehicles, Department of Health, Education, and Welfare, National Center for Air Pollution Control, Battelle Memorial Institute, 1968.

TABLE 15
DATA ON SEVERAL AUTOMOTIVE STEAM ENGINES EITHER BUILT OR STUDIED SINCE 1950

Developer or Researcher	Engine Reference	Rating hp at rpm	Rated Pressure, psia / Temperature, F	Specific Weight lb/hp(s)	Specific Volume ft^3/hp(s)	Maximum Efficiency, percent	Start-Up Time[a], sec	Torque Ratio[c]	Power-Surge Ratio[c]	Specific Cost, \$/hp(s)
Williams Engine Co.	49	150 at 2400	1000 / 1000	5.4	0.14	--	PO<30	3.4	1.67	44
McCulloch Corp.	50	120 at 1200	2000 / 900	8.0	--	23	FPO<30	--	1.25	--
Gibbs Hosick Trust	51	60 at 2500	2000 / 850	--	--	--	--	2.3	--	--
Richard J. Smith	52	250 at 6000	1000 / 700	--	--	28	FPO-14	1.8	--	--
Thermo Electron Engineering Corp.	53[d]	100 at 1680	1200 / 1250	5.0	--	28	--	1.1	--	--
Microtech Research Co.	54[d]	175	1500 / 1100	17.2	0.67	16	FPO-500	--	--	--
General Dynamics/Convair	55[d]	500	1200 / 1000	--	0.16	22	--	--	1.5-2.0	--
S. W. Gouse, Jr.	25, 56[d]	--	--	5-10	--	25-30	--	--	--	3(?)
Battelle/Northwest	57[d]	50	2500 / 670	--	--	24	FPO<10	--	--	--

(a) PO = time to power output; FPO = time to full power output.

(b) Torque ratio = the ratio of stall torque to rated torque.

(c) Power-surge ratio = the ratio of short-term, "burst", power to continuous rated power.

(d) Paper studies only.

(3) Stirling Cycle Engines

Stirling cycle engines have received renewed interest as power sources in recent years. In fact, as early as World War II, the N. V. Phillips Laboratories of Eindhoven, Netherlands undertook the development[17] of a modern version of the Stirling engine as a means of producing electrical power in remote areas. The principal developments in the United States have been carried out by the General Motors Corporation under a licensing agreement with Phillips. Performance parameters of typical devices manufactured by Phillips and General Motors are shown in Table 16.

The Battelle study, in its review of the current and projected state-of-the-art of Stirling Cycle devices, concluded that:

> ".... Thus the Stirling engine is considered to be a potentially acceptable vehicular power plant. In relation to present passenger car engines, the primary factors limiting the use of Stirling engines are the relatively high first cost, weight, and size and the large radiator that is required..... "

In its study[18] of energy sources for undersea applications, the National Academy concluded that:

> "Both fuel cells and the Stirling reciprocating dynamic converters show significant potential for use as an undersea energy system. A rational choice can be made only after a detailed study and comparison of many missions and uses. Since many millions of dollars are involved in developing and qualifying either converter, final choice should be based on such a detailed study and comparison. It is recommended that parallel programs in both systems be pursued until the final choice is made. "

17/ Battelle Study, Ibid.

18/ NAS-NRC Study, op. cit.

TABLE 16
TYPICAL STIRLING-ENGINE DATA

Developer	Model No.	No. of Cylinders	Rating, hp(s) at rpm	Max. Brake Thermal Efficiency, percent	Envelope Volume[a], ft^3	Specific Volume[a], $ft^3/hp(s)$	Weight[a], lb	Specific Weight[a], lb/hp(s)
GM Research	GPU-2	One	7.5 at 3600	23	3.04	0.40	90[b]	12.0
GM Research	GPU-3	One	10.0 at 3000	27	4.89	0.49	188	18.8
Philips	3015	One	40.0 at 2500	39	6.40	0.16	550	13.8
GM Electromotive	8015	Four	380 at 1500	30	130.00	0.34	5000	13.2
Philips	Marine	Four	120 at 3000	40 (calc.)	23.20	0.19	725	6.0
GM Allison	PD-67	One	7 at 3000	30	3.50[c]	--	186[c]	--

(a) Reciprocating unit only, including combustor and preheater. Excludes fuel pump, water pump, combustion air blower, motor, radiator and fan assembly, working-fluid reservoir, starter motor, ignition system, and fuel control.

(b) Excludes flywheel also.

(c) Includes 4 hp(e) generator.

In its discussion of Stirling cycle engines, the USAMERDC report states that:

> "Stirling cycle power plants in semi-militarized configuration have been run for over 1,000 hours without major difficulty. Fundamentally, there are no problems with the Stirling cycle that have not been solved to the extent that practical hardware can be built and operated. The hardware is a complex mechanical system requiring strong design discipline in order to seal the working fluid and maintain good control over the system under dynamic operating conditions."

The views[19] of still another analyst are somewhat more sobering, however:

> "There are many difficulties in making a practical Stirling engine. High temperatures are essential to keep the size of the engine down, but this makes lubrication a serious problem because of the "dry" high-temperature operating conditions. Also the working lifetime of such a machine in the field is not likely to be more than a few hundred hours between overhauls unless a radical breakthrough in design is forthcoming."

4. WIND-POWERED ELECTRIC GENERATORS[20]

Wind-powered electric devices have not been significantly pursued as energy sources for at least two decades. Wind-driven generator sets for farm power are still being manufactured, however. The potential of these devices for Limited War Laboratory application is difficult to assess, primarily because of the unavailability of worldwide data as to the energy source.

19/ "Power for Remote Areas," Harry Z. Tabor, International Science and Technology, May 1967.

20/ Battelle Study, op. cit.

5. THERMIONIC CONVERTERS[21]

Thermionic conversion of heat to electricity is based upon application of the Edison effect—the escape of electrons from a heated surface, termed the emitter. A second electrode, termed the collector, is placed near the emitter to collect the escaping electrons. The number of electrons emitted increases exponentially as the temperature of the emitting body increases. Unfortunately, the device is space-charge limited. Space-charge compensation consists of introducing positive ions and reducing the interelectrode distance.

The following characteristics are advantages of thermionic converters:

- There are no moving parts
- Operating temperatures up to 4000°F are possible
- Waste heat can be rejected at high temperatures
- The power-to-weight ratio is relatively high.

Experience with practical applications is extremely limited. However, flame-heated converters have operated for more than 300 hours. Power densities of two-to-ten watts per square centimeter and efficiencies of four-to-nine percent have been attained.

Flame-powered devices in the full range of power outputs of interest to the Limited War Laboratory have been designed but only prototype modular units of low output have been manufactured. Specific performance data on these units is considered extremely experimental in nature, and the state-of-the-art appears to offer little promise in satisfying Limited War Laboratory requirements, at least in the short-run.

21/ Battelle Study, op. cit.

IV. COMPARATIVE DATA

An advanced draft copy of a study on silent power sources, supplied by the USAMERDC Electrotechnology Laboratory, is an outstanding source of comparative evaluative data concerning power sources for remote areas. Unfortunately, these data do not cover the full range of devices reviewed in this survey, nor is the objective of USAMERDC the same as that of LWL. However, the USAMERDC report is the most comprehensive of those available and is based upon actual test and operating experience with candidate devices. Accordingly, extracts from the comparative tables contained in the USAMERDC report are reproduced on the following pages.

TABLE 17

Audibility Data Sheet

(Tabulated data indicate distance in meters at which source is inaudible vs. jungle ambient background)

System / KW →	0.5		1.5		3.0		5.0		10.0		15.0	
Years From Present →	2-5	10-20	2-5	10-20	2-5	10-20	2-5	10-20	2-5	10-20	2-5	10-20
SILENCED ENGINE-GENERATOR	100	100	100	100	100	100	100	100	100	100	100	100
STIRLING CYCLE	100	50	100	50	100	50	100	50	100	100	100	100
CLOSED RANKINE CYCLE	50	30	100	60	100	70	100	80	100	100	100	100
CLOSED BRAYTON CYCLE	100	100	100	100	100	100	100	100	100	100	100	100
THERMOELECTRIC	100	40	100	50	100	75	100	100	100	100	100	100
OPEN BRAYTON CYCLE SILENCED	100	100	100	100	100	100	100	100	100	100	100	100
LOW TEMPERATURE FUEL CELL ACID	30	30	50	30	50	30	75	50	100	100	100	100
LOW TEMPERATURE FUEL CELL ALKALINE	50	30	60	30	100	50	100	100	100	100	100	100
HIGH TEMPERATURE FUEL CELL	50	30	50	30	70	50	70	50	100	100	100	100

TABLE 18

Weight Data Sheet

(Units of tabulated data are pounds)

System KW →	0.5		1.5		3.0		5.0		10.0		15.0	
Years From Present →	2-5	10-20	2-5	10-20	2-5	10-20	2-5	10-20	2-5	10-20	2-5	10-20
SILENCED ENGINE-GENERATOR	165	148	300	270	885	796	1450	1305	2200	1980	4550	4095
STIRLING CYCLE	150	125	275	240	400	350	550	460	985	770	1405	1140
CLOSED RANKINE CYCLE	65	50	145	110	240	180	360	255	740	465	1105	680
CLOSED BRAYTON CYCLE	200	180	260	220	320	280	400	330	650	510	870	675
THERMOELECTRIC	50	42	140	120	270	240	470	390	995	795	1385	1180
OPEN BRAYTON CYCLE SILENCED	200	95	225	110	275	140	325	190	410	295	530	410
LOW TEMPERATURE FUEL CELL ACID	100	60	200	115	525	300	800	450	1500	820	2200	1250
LOW TEMPERATURE FUEL CELL ALKALINE	100	80	200	150	500	375	700	560	1360	980	1945	1400
HIGH TEMPERATURE FUEL CELL.	350	200	450	280	850	500	1200	700	2100	1100	3000	1500

TABLE 19
VOLUME DATA SHEET
(Units of tabulated data are in cubic feet)

System kW →	0.5		1.5		3.0		5.0		10.0		15.0	
Years From Present →	2-5	10-20	2-5	10-20	2-5	10-20	2-5	10-20	2-5	10-20	2-5	10-20
Silenced Engine-Generator	11	11	11	11	22	22	34	34	61	61	102	102
Stirling Cycle	7	5	12	10	16	13	20	16	32	25	44	36
Closed Rankine Cycle	5	4	9	8	14	12	20	17	33	26	44	33
Closed Brayton Cycle	12	9	16	11	20	14	25	17	39	25	49	32
Thermoelectric	4	4	9	8	16	14	26	20	45	35	62	49
Open Brayton Cycle (Silenced)	10	5	11	6	13	7	15	9	18	12	24	18
Low-Temperature Fuel Cell (Acid)	3	2	7	4	18	10	27	15	48	28	70	40
Low-Temperature Fuel Cell (Alkaline)	4	2	9	5	18	13	27	20	50	36	69	50
High-Temperature Fuel Cell	14	10	20	13	33	20	40	24	60	33	75	40

TABLE 20
FUEL-CONSUMPTION DATA SHEET
(Units of tabulated data are in pounds of fuel per hour at rated load)

System kW →	0.5		1.5		3.0		5.0		10.0		15.0	
Years From Present →	2-5	10-20	2-5	10-20	2-5	10-20	2-5	10-20	2-5	10-20	2-5	10-20
Silenced Engine-Generator	1.6	1.6	3.4	3.4	5.3	2.7	8.8	4.1	15.0	8.2	9.4	9.4
Stirling Cycle	0.8	0.7	1.5	1.4	2.8	2.6	4.6	4.2	8.3	7.7	11.8	11.0
Closed Rankine Cycle	1.6	1.2	4.0	3.0	6.6	5.0	9.7	7.7	16.0	13.0	31.4	17.3
Closed Brayton Cycle	1.5	1.2	2.6	2.3	5.8	5.2	8.5	7.5	14.8	12.8	21.5	17.2
Thermoelectric	2.5	1.8	5.4	3.9	9.8	6.9	15.7	11.0	30.9	31.0	46.0	31.0
Open Brayton Cycle (Silenced)	3.5	2.5	6.0	4.0	8.0	6.0	10.0	8.0	18.0	15.0	23.0	20.0
Low-Temperature Fuel Cell (Acid)	.46	.31	1.2	.8	2.8	2.0	4.0	3.0	7.4	5.6	11.4	8.7
Low-Temperature Fuel Cell (Alkaline)	.35	.33	.9	.8	2.2	1.9	3.6	2.9	6.9	5.4	10.2	8.0
High-Temperature Fuel Cell	1.0	0.7	2.3	1.4	4.6	2.4	6.3	3.1	10.8	5.0	15.0	7.0

TABLE 21

MISSION WEIGHT DATA SHEET

(Tabulated data indicate total weight in pounds for 72-hour mission)

System kW →	0.5		1.5		3.0		5.0		10.0		15.0	
Years From Present →	2-5	10-20	2-5	10-20	2-5	10-20	2-5	10-20	2-5	10-20	2-5	10-20
Silenced Engine-Generator	322	305	628	598	1403	1206	2224	1715	3520	2800	5367	4915
Stirling Cycle	229	189	425	383	675	611	981	832	1732	1464	2095	2142
Closed Rankine Cycle	222	168	528	400	883	666	1208	949	2172	1611	2996	2206
Closed Brayton Cycle	350	298	521	449	885	791	1152	1010	1956	1642	2768	2193
Thermoelectric	293	224	665	506	1217	915	1880	1392	3710	2657	5397	3902
Open Brayton Cycle (Silenced)	522	338	769	468	991	684	1206	906	1985	1616	2535	2172
Low-Temperature Fuel Cell (Acid)	154	93	318	194	800	497	1158	736	2173	1323	3231	2016
Low-Temperature Fuel Cell (Alkaline)	136	114	296	227	721	564	1029	839	1997	1459	2849	2116
High-Temperature Fuel Cell	453	264	679	423	1297	736	1794	993	3088	1540	4320	2144

TABLE 22

MISSION VOLUME DATA SHEET

(Tabulated data indicate total volume in cubic feet for 72-hour mission)

System kW →	0.5		1.5		3.0		5.0		10.0		15.0	
Years From Present →	2-5	10-20	2-5	10-20	2-5	10-20	2-5	10-20	2-5	10-20	2-5	10-20
Silenced Engine-Generator	14.7	14.7	19.0	19.0	35.1	32.5	55.4	44.5	97.3	82.0	124.8	123.0
Stirling Cycle	9.0	8.0	16.0	14.0	23.0	20.0	31.2	27.2	54.4	47.4	66.4	59.6
Closed Rankine Cycle	8.5	7.0	18.0	15.0	30.0	24.0	43.6	39.4	77.8	49.6	100.0	77.8
Closed Brayton Cycle	16.0	12.0	23.0	17.0	34.0	27.0	47.4	39.4	75.8	58.6	105.0	76.8
Thermoelectric	10.0	8.5	22.0	18.0	39.0	31.0	70.8	53.6	123.4	91.0	174.0	127.4
Open Brayton Cycle (Silenced)	21.2	11.0	26.2	17.0	35.4	22.2	39.4	31.4	62.8	48.6	80.0	66.8
Low-Temperature Fuel Cell (Acid)	5.0	2.5	10.4	6.0	25.0	15.0	38.2	26.2	70.4	42.4	103.6	62.4
Low-Temperature Fuel Cell (Alkaline)	4.8	3.0	11.5	7.0	24.0	18.0	37.2	31.2	72.4	50.6	94.6	72.4
High-Temperature Fuel Cell	17.0	12.0	26.0	17.0	44.0	26.0	62.4	35.2	93.6	45.4	12.8	62.4

TABLE 23
TIME-BETWEEN-OVERHAUL DATA

(Tabulated data indicate hours of operation between overhaul)

SYSTEM KW →	ALL POWER SIZES	
Years from Present →	2-5	10-20
SILENCED ENGINE-GENERATOR	1500	5000
STIRLING CYCLE	1500	2500
CLOSED RANKINE CYCLE	2500	2500
CLOSED BRAYTON CYCLE	3000	6000
THERMOELECTRIC	1500	2500
OPEN BRAYTON CYCLE (SILENCED)	3000	6000
LOW-TEMPERATURE FUEL CELL (ACID)	2500	5000
LOW-TEMPERATURE FUEL CELL (ALKALINE)	2500	5000
HIGH-TEMPERATURE FUEL CELL	2500	5000

TABLE 24
LIFE CYCLE POWER COST DATA (Based on 3KW-AC unit)

(Tabulated data are dollars per KW hour)

SYSTEM / KW →	ALL POWER SIZES	
Years from Present →	2-5	10-20
SILENCED ENGINE-GENERATOR	0.69	0.31
STIRLING CYCLE	1.78	0.51
CLOSED RANKINE CYCLE	1.38	0.51
CLOSED BRAYTON CYCLE	1.54	0.60
THERMOELECTRIC	3.90	1.30
OPEN BRAYTON CYCLE (SILENCED)	1.01	0.38
LOW-TEMPERATURE FUEL CELL (ACID)	1.70	0.46
LOW-TEMPERATURE FUEL CELL (ALKALINE)	2.11	0.63
HIGH-TEMPERATURE FUEL CELL	1.85	0.34

TABLE 25
ESTIMATED DEVELOPMENT COST

(Prototype to type-classification - values in table expressed in millions of dollars)

SYSTEM	KW →	ALL POWER SIZES	
Years from Present →		2-5	10-20
SILENCED ENGINE-GENERATOR		0.5	1.5
STIRLING CYCLE		2.0	4.2
CLOSED RANKINE CYCLE		3.5	5.5
CLOSED BRAYTON CYCLE		8.0	10.0
THERMOELECTRIC		2.0	4.0
OPEN BRAYTON CYCLE (SILENCED)		6.0	10.0
LOW-TEMPERATURE FUEL CELL (ACID)		11.0	15.0
LOW-TEMPERATURE FUEL CELL (ALKALINE)		9.0	13.0
HIGH-TEMPERATURE FUEL CELL		10.0	15.0

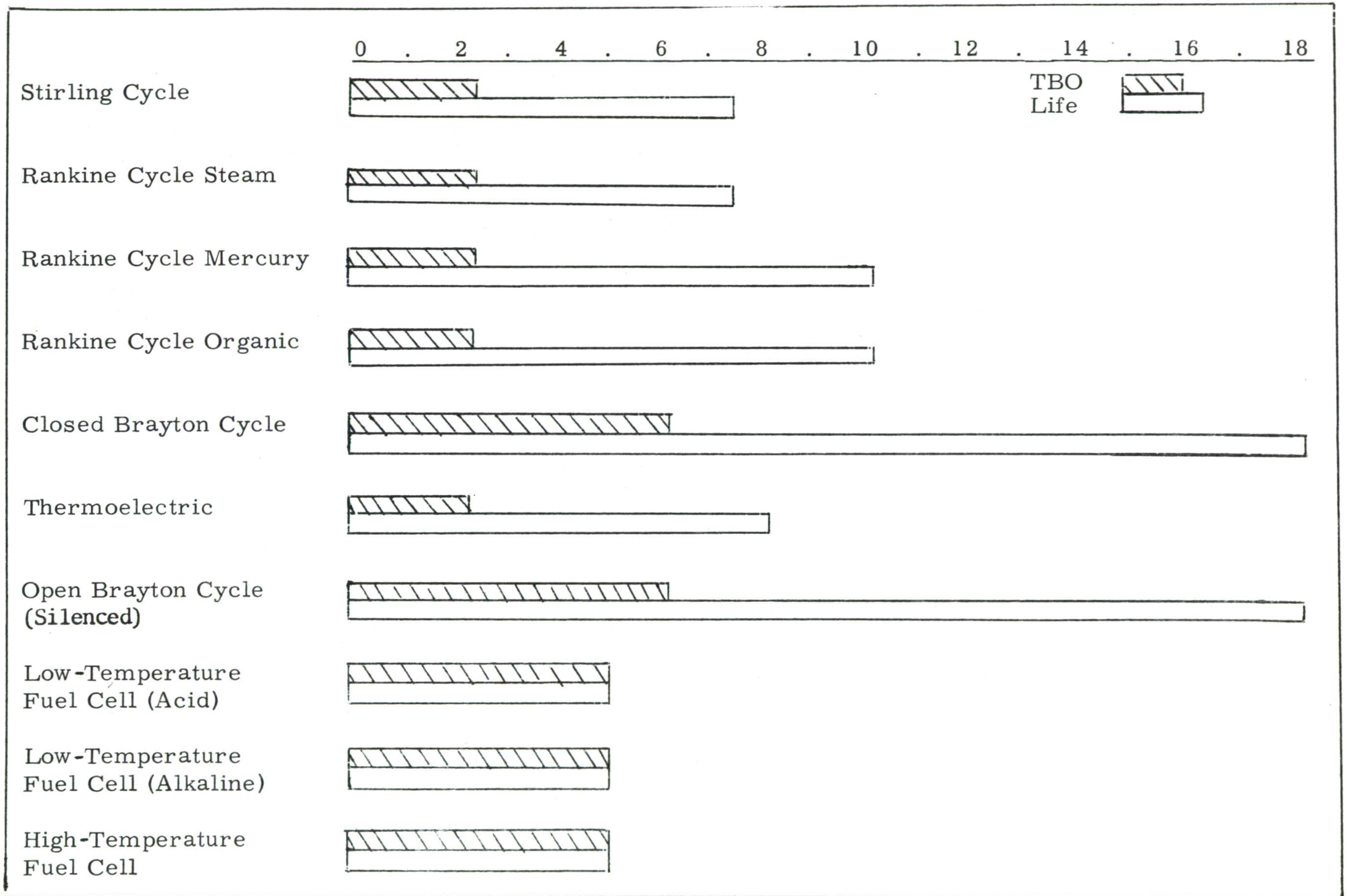

FIGURE 5. PROJECTION OF OPERATING TIME (IN THOUSANDS OF HOURS)-BETWEEN-OVERHAUL (TBO) AND IN SERVICE LIFE FOR MID-TERM FUTURE (10-20 YEARS)

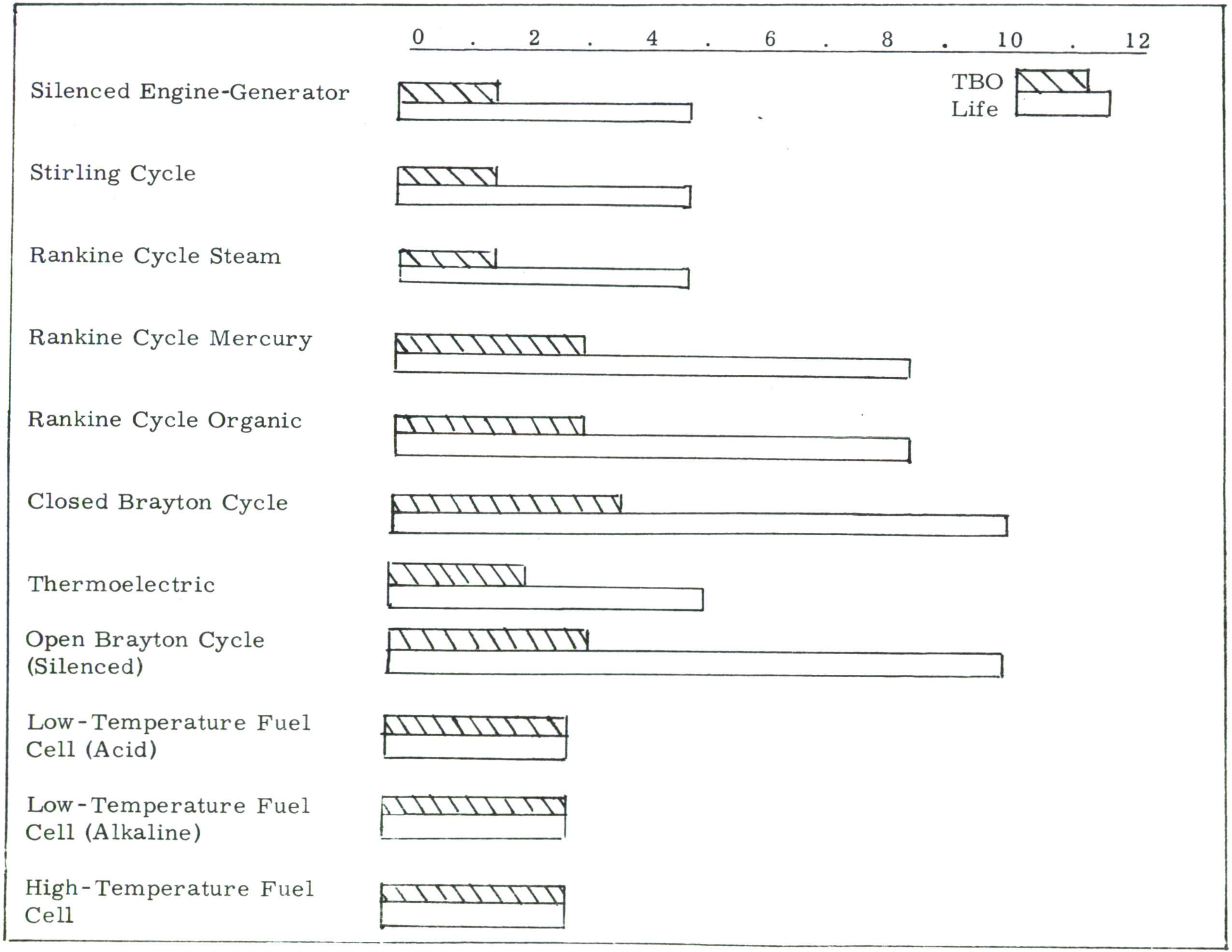

FIGURE 6. PROJECTION OF OPERATING TIME (IN THOUSANDS OF HOURS)-BETWEEN-OVERHAUL (TBO) AND IN SERVICE LIFE FOR THE NEAR-TERM FUTURE (2-5 YEARS)

V. CONCLUSIONS

There are several candidate devices having demonstrated capability and potential as power sources for remote areas in the range of power outputs from a few watts to two or three kilowatts. There is, however, a limited amount of test and operational experience, particularly commercial applications and military experience, with all of these candidates except for the general purpose Military Standard family of reciprocating-engine generator sets.

In the immediate future, the present general purpose Military Standard family of reciprocating-engine generator sets, preferably in silenced configuration, continues to appear attractive for military applications. Technology associated with thermoelectric devices make them attractive for relatively near-term remote area small power applications. They share with external combustion thermodynamic engines the ability to use indigenous fuels. Other factors tending to reduce logistics associated with their use are favorable, such as improving reliability and minimal maintenance. For the longer term, the fuel cell appears to offer many advantages for small power applications. For larger power requirements, a number of external combustion thermodynamic engines appear to be good candidates for remote area power generation.

Of the opinions expressed by experts in the field, those of the USAMERDC Electrotechnology Laboratory are given considerable credence. These opinions are that, from the standpoint of silent operation for military applications, closed-cycle Rankine devices of 500 watts to 3 kilowatts have considerable promise for the short-run, while fuel cells probably possess greater potential in the long-run. However, on the basis of the data acquired during this survey, it is concluded that no single class of device appears to offer potential so superior as to warrant its development to the exclusion of all others by the Limited War Laboratory. Selection of a single or set of candidates for further development can be made only from a firm and comprehensive definition of requirements for power sources in the range of power outputs considered.

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